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# DESIGN, DEVELOPMENT, AND OPERATION OF A DIRECTIONAL SHEAR CELL

by

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<p>→ The directional shear cell (DSC) prototype was commissioned by the US Army Engineer Waterways Experiment Station (WES) with the aims of carrying out basic research and eventually the routine testing of undisturbed samples from the field under stress paths including controlled rotation of the principal stress axes. The new design evolved from experimentation and a wide range of discussions between WES personnel and the research team at University College, London, England.</p> <p>→ Advances were made from previous versions of the DSC. For example, in this prototype, testing is completely automated (including cyclic tests) with the capability to rotate the principal stress axes through 360 deg. The new version also has a significantly higher stress capacity. The aim throughout apparatus development was to produce a device which would be easy to work with. In particular, the original apparatus design required the operator to use judgement in adjusting the positions of the normal-pressure bags and the</p> <p style="text-align: right;">(Continued)</p>					
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alignment of the shear sheets as the specimen deformed. It was considered very important to make these adjustments automatic and therefore objective.

There are many possible research areas that can be pursued using the new DSC. An important area for practical applications is assessing the performance of various types of constitutive models for soils by imposing complex stress paths that replicate prototype loading. Areas of research for improvement of the apparatus include quality of strain measurement and automation, comparative studies of other shear apparatuses, lubrication, and specimen preparation.

## PREFACE

This investigation was conducted as part of the work unit Behavior of Soil under a Generalized Stress Path, authorized by the US Army Corps of Engineers, under Civil Works Work Unit 32343, "Soil Behavior Under Generalized Stress Paths." The investigation was conducted at University College, London, England (UCL) and the US Army Engineer Waterways Experiment Station (WES) during the period of fiscal years 1985 to 1988. The UCL portion was carried out under Contract Number DAJA-87-C-0030.

Design and construction of the directional shear cell were performed by Professor T. Dunstan, Mr. F. Cutler, Mr. J. Ford, and Mr. J. R. Pulsford under the direction of Professor J. R. F. Arthur at UCL. Fabrication of the apparatus at UCL was aided by Messrs. D. W. Vale and L. Wade. Modifications to the device and testing procedures were performed at WES by Mr. Pulsford, Dr. J. F. Peters, and Mr. D. A. Leavell.

Dr. Peters served as the Principal Investigator for the project. Research at WES took place under the direction of Dr. W. F. Marcuson III, Chief, Geotechnical Laboratory (GL), and under the general supervision of Mr. C. L. McAnear (ret), Chief, Soils Mechanics Division (SMD), Dr. D. C. Banks, Chief, Soil and Rock Mechanics Division (SRMD), and Mr. G. P. Hale, Chief, Soils Research Center (SRC). Mr. Richard F. Davidson was the USACE Technical Monitor.

COL Larry B. Fulton, EN, is Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

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# DESIGN, DEVELOPMENT, AND OPERATION OF A DIRECTIONAL SHEAR CELL

## PART I: INTRODUCTION

### Background

1. The prototype design of the directional shear cell (DSC) was commissioned by the US Army Engineer Waterways Experiment Station (WES) with the aims of carrying out basic research and eventually the routine testing of undisturbed samples under stress paths including controlled rotation of the principal stress directions. The DSC was chosen because it has a practicable prismatic specimen shape as opposed to that of the hollow cylinder apparatus. Although most DSC testing has been concerned with sand, there has been an appreciable amount of testing of clay, for instance in basic research at the Massachusetts Institute of Technology (MIT) on resedimented Boston Blue Clay (Jamolkowski et al. 1985, Germaine 1982). Thus, it is known that the DSC can be used to obtain high-quality shear tests on this soil type.

### Loading Capabilities

#### Stress parameters

2. The distinguishing feature of the DSC (versus simple shear and torsional shear devices) is the ability to control normal and shear stresses independently. The normal and shear stresses are applied to the four vertical faces of a prismatic specimen, whereas the normal stress that simulates plane-strain conditions is imposed on the two horizontal faces. The principal stress direction is controlled by varying the normal stresses  $\sigma_a$  and  $\sigma_b$ <sup>1</sup> and shear stresses  $\tau_a$  and  $\tau_b$  on the specimen boundary. However, stresses are reported in cartesian coordinates  $\sigma_x$ ,  $\sigma_y$ , and  $\tau_{xy}$ . Stresses of the  $x - y$  system are related to those of the  $a - b$  system by relationships that account for specimen distortion which will be discussed later. To simplify the present discussion  $\sigma_x$ ,  $\sigma_y$ , and  $\tau_{xy}$  will be treated as applied stresses.

3. Figure 1a illustrates how the applied stresses ( $\sigma_x$ ,  $\sigma_y$ , and  $\tau_{xy}$ ) are related to the principal stresses,  $\sigma_1$  and  $\sigma_3$ , by the angle  $\psi$ . The relative magnitudes of the applied normal and shear stresses determine the size of the angle  $\psi$ . The relationship is given by the equations of Mohr's circle:

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<sup>1</sup>Subscripts a and b signify contact stresses on the specimen faces which may not remain orthogonal throughout the course of the test.

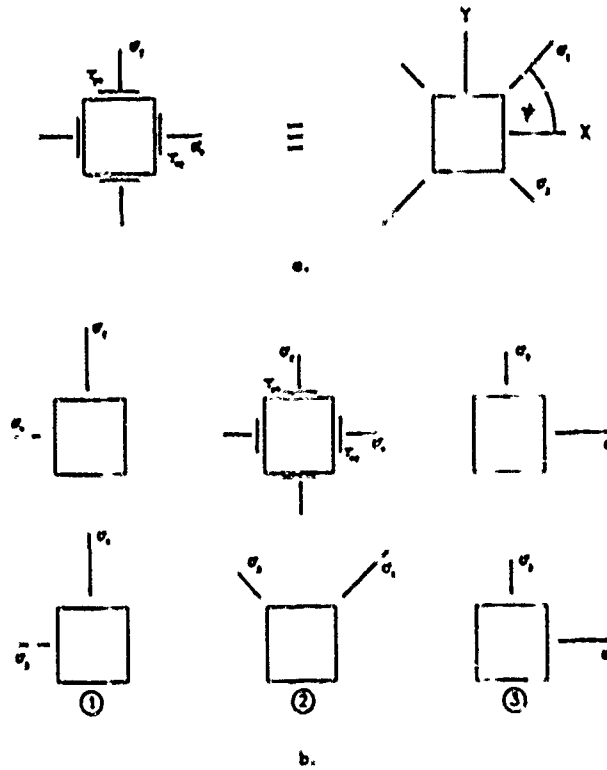


Figure 1: Stresses applied to DSC specimens

$$\begin{aligned}\sigma_x &= \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3) \cos 2\psi \\ \sigma_y &= \frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3) \cos 2\psi \\ \tau_{xy} &= \frac{1}{2}(\sigma_1 - \sigma_3) \sin 2\psi\end{aligned}$$

Figure 1b shows that any major principal stress direction can be achieved, from plane-strain compression (1) through maximum shear (2) to extension (3), by changing the relative magnitudes of the normal and shear stresses.

4. Presently, all DSC devices apply shear within one plane such that the intermediate principal stress ( $\sigma_2$ ) is orthogonal to the shearing plane. Configuration of the DSC is such that the intermediate principal stress is either applied through a flexible membrane, as in a controlled-stress configuration, or simply measured as for a plane-strain configuration. The controlled-stress approach has been adopted in the new design but because the strain capacity in the intermediate principal stress direction is generally limited, nearly plane-strain conditions must be maintained for the controlled-stress configuration. To achieve plane-strain conditions,  $\sigma_2$  is maintained according to

$$\sigma_2 = b(\sigma_1 - \sigma_3) + \sigma_3$$

where a value of  $b \approx 0.3$  has been found from experience to maintain the plane-strain condition.

5. Whether operating under plane-strain conditions or maintaining a constant  $b$ , stress paths are controlled through three quantities. These quantities can be specified in terms of the three components  $\sigma_x$ ,  $\sigma_y$ , and  $\tau_{xy}$ , as might be the case for tests based on stress paths derived from practical problems. For research tests, the principal stress values,  $\sigma_1$  and  $\sigma_3$ , along with the rotation angle  $\psi$  are often found more suitable because the object of these tests is to isolate the effects of rotating the principal axes. When testing sand at low stresses the frictional nature of the sand plays a primary role in the experimental design and the shear-stress level is expressed in terms of the principal stress ratio  $R = \sigma_1/\sigma_3$ .<sup>2</sup> This report follows the literature on the DSC and describes stress states in terms of  $R$ ,  $\sigma_3$ , and  $\psi$  whereby the equations of Mohr's circle become:

$$\begin{aligned}\sigma_x &= \frac{1}{2}\sigma_3 [(R+1) + (R-1)\cos 2\psi] \\ \sigma_y &= \frac{1}{2}\sigma_3 [(R+1) + (R-1)\cos 2\psi] \\ \tau_{xy} &= \frac{1}{2}\sigma_3 (R-1)\sin 2\psi\end{aligned}$$

### Improved loading capabilities

6. Previous versions of the University College, London, England (UCL) DSC, as described by Arthur et al. (1981), had three serious disadvantages: (a) limited to very low stress levels for most geotechnical applications, (b) large shear-stress hysteresis in cyclic loading, and (c) the use of operator judgement to manually position the normal-pressure bags and align the shear sheets. A new shear-sheet design overcomes the first two problems. The third problem was overcome by a mechanical design that features automatic alignment of shear sheets and normal-pressure bags. In addition, the stress application capabilities have been improved to permit more generalized loading histories. For example, principal stress directions can be rotated through 360 deg without changing the sense of the rotation or the principal stress values.

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<sup>2</sup>The pore pressure in the DSC is always maintained at zero, therefore all stresses are effective. The conventional use of primes to denote effective stress quantities has not been adopted for this report.

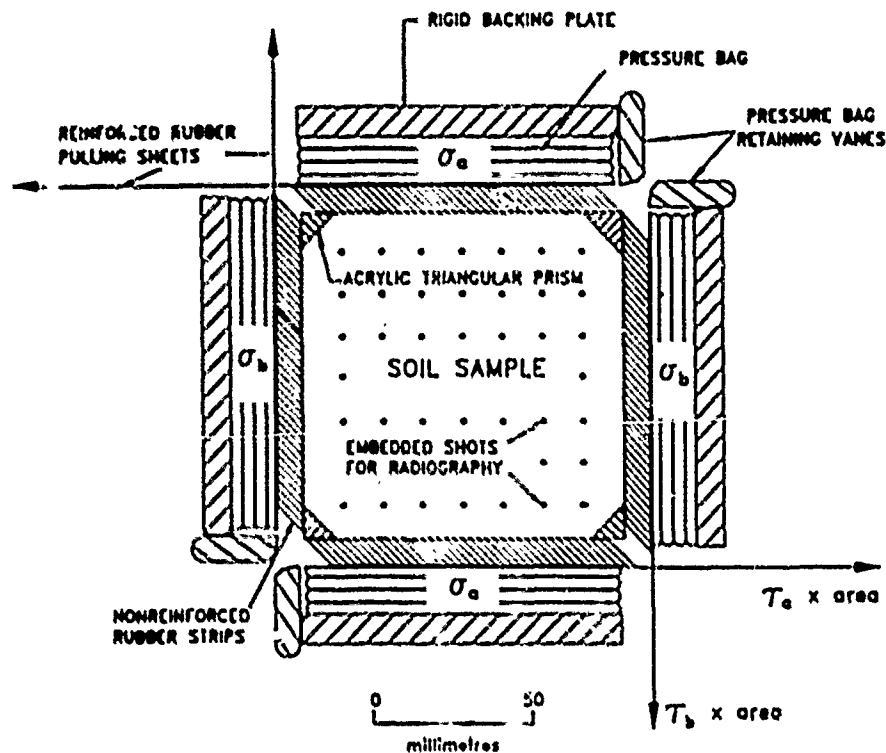


Figure 2: Horizontal cross section of the original UCL DSC design

7. The new design evolved from experimentation and discussions between WES personnel and the research team at UCL. An example of this interactive process was the decision to carry out undrained tests using the null method in which the total stresses are adjusted to keep the pore water pressure in the specimen at zero. This decision was a result of experiments at UCL which showed that the edge confinement in DSC specimens did not maintain the test specimen at a constant volume when positive pore water pressure developed.

### Boundary Stress Application

#### Original design

8. All UCL DSC's are stress-controlled devices employing a flexible-membrane loading system to achieve uniform boundary stresses. Figure 2 shows a cross section of the original DSC (Arthur et al. 1981) and illustrates the method used to apply normal and shear stresses to the four vertical faces of the cubical test specimen (100-mm cube). The rubber membrane which encapsulates the soil specimen is in direct contact with the shear sheets which apply the shear stresses. The shear sheets consist of rubber pulling strips attached to a thin latex sheet which bonds under pressure to the specimen membrane. These rubber strips can stretch 300 percent and

distribute the shear stress evenly over the vertical faces of the specimen. A thin layer of sand glued to the inner surface of the specimen membrane improves traction between it and the specimen. The shear forces are applied by hydraulic piston assemblies which are attached to the shear sheets through flexible but inextensible connecting sheets. Two sets of reinforced-rubber pressure bags, of a concertina form, transmit  $\sigma_x$  and  $\sigma_y$  through the shear sheets onto the specimen. A uniform layer of lubrication is used between the pressure bags and shear sheets to minimize friction in the shearing direction.

9. The horizontal specimen faces which correspond to the intermediate stress direction are restrained by rigid platens. To minimize end friction a translucent lubricant is also used between the rigid end platens and the specimen. A glass top platen allows deformation of the specimen's top face to be observed directly. The strain distributions within the specimen are calculated from the displacements of regularly spaced markers such as those shown in Figure 2 (embedded lead or tungsten shot). If radiography is used, these markers are placed in the central plane of the specimen. Alternatively, photography can be used if a grid system is inscribed on the top surface of the specimen's membrane (Wong and Arthur 1985a).

## New design

10. The development of a new design for boundary load application depended on finding an alternative to the latex-based construction material used for the shear sheets. The possibility of using silicon rubber for manufacturing pressure bags and shear sheets was investigated; this technique is used at the University of Colorado (CU), Boulder, CO (Budiman 1985). There is an obvious advantage to using silicon rubber since it can be readily molded. However, the design concept used for the high-capacity shear sheets combines parts consisting of different materials. In particular, positive adhesion between the pulling strip and the specimen membrane is essential to obtaining the best distribution of surface shear on the specimen faces. The CU design uses one-piece pulling strips which transfer shear to the specimen through a frictional interface which is not reliable at higher stress levels. It proved impossible to achieve adhesion under pressure between either silicon rubber surfaces or silicon rubber/natural rubber interfaces; therefore, the use of silicon rubber was abandoned for the present design. As an alternative, a light, strong sailcloth (a tightly woven inextensible Dacron fabric) was found to bond extremely well to ordinary latex rubber providing the basis for a dramatic increase in the maximum stress level of DSC tests. The sailcloth can be easily cut into intricate shapes with a low-wattage (25-watt) soldering iron making fabrication of the shear sheets relatively simple. As a disadvantage, sailcloth lacks the flexibility needed for stress control requiring the shear sheet to be built up of a daisy-chained

system of Dacron-latex components as described in detail in Part II.

### **Material Tested During Developmental Phase**

11. Leighton Buzzard sand was used during the development of the daisy-chain DSC. All developmental decisions were based on test results from this material. Leighton Buzzard sand is subrounded, uniformly graded in the particle size range from 0.65 to 0.8 mm, and has a specific gravity of 2.66. When pluviated through air it has an  $e_0$  value of 0.52 when dense and 0.73 when loose. Throughout the report, when the density of a test specimen is referred to as dense or loose, these respective void ratios are implied.

12. Leighton Buzzard sand has been used extensively by UCL and in other test programs (Sture, Alawi, and Ko 1988 and Bekenstein 1980) providing a large data base for comparison.

## PART II: APPARATUS DEVELOPMENT AND CAPABILITIES

### Specimen Configuration

13. The specimen configuration is dependent on two requirements; it must be small enough to allow testing of undisturbed samples of a reasonable size (125-mm- (5-in.-) diam boring) but large enough to give uniform strains in its central area. The 100-mm cube used in the old UCL DSC design and the 170-mm cube used at CU (Budiman 1985), were large enough to achieve uniform strains but too large to allow specimens to be trimmed from a standard 125-mm-diam tube. To determine if a smaller specimen size could be used, a plane-strain experiment was performed on a 100-mm-thick specimen having a 75- by 75-mm section in the plane of shear. To save time, the original apparatus was used with shear sheets properly sized to fit this smaller specimen. The uniformity of strains from this trial test was unsatisfactory, which indicated that a larger plane-strain section was needed. Therefore, without further testing, a criterion that the specimen have a minimum 100- by 100-mm plane-strain section was adopted.

14. As a compromise, a 100- by 100- by 75-mm prismatic shape was used. This shape provided the specimen dimensions required for strain uniformity and, because its side-to-thickness ratio was 4 to 3, specimens could be trimmed from 125-mm-diam tube samples. A limitation of this configuration is the inability to fully explore inherent anisotropy of undisturbed materials. However, having the plane-strain direction perpendicular to the typical direction for soil deposition in undisturbed samples provides the most common orientation of practical interest. A comparison of data obtained from DSC specimens having 100- and 75-mm thicknesses is shown in Figure 3. These data support the assumption that the reduction in thickness to 75 mm makes no discernible difference in results, and support the idea that a cubical shape is not necessary.

### Lubrication

15. Like the old UCL DSC design, lubrication is an integral part of the apparatus's design. A uniform 3.0-mm-thick layer of grease is needed to avoid excessive frictional drag between parts of the apparatus and the specimen. Grease is used mainly between the specimen face and the glass window in the top platen and between the shear sheets and the normal-pressure bags. The need for effective lubrication is especially important at low stress levels where frictional forces, in the absence of proper lubrication, can become large relative to applied loads. It has been demonstrated at UCL that an effective lubricant is a mixture of polytetrafluoroethylene (PTFE)

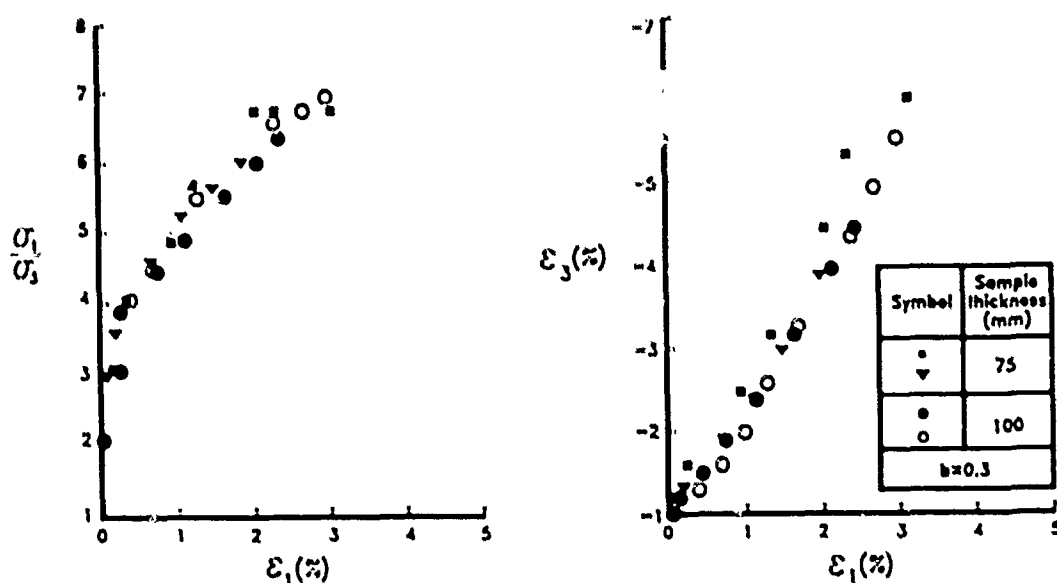


Figure 3: Comparison of stress-strain data for dense Leighton Buzzard sand from DSC specimens having thicknesses of 100 and 75 mm

powder and high-viscosity silicon grease (Arthur et al. 1986).

### Daisy-Chain Shear Sheets

16. The goal of the new shear-sheet design is to achieve a higher shear stress capacity without loss of the flexibility needed for stress control. As in the original shear-sheet design, the shear stress is transferred to the specimen membrane by a thin shear sleeve of latex rubber which adheres to the membrane when under pressure from the normal-pressure bags. Thin strips of rubberized sailcloth are glued to the outer surface of this sleeve replacing the nonreinforced stretching rubber strips which were shown in Figure 2. The stretching element in the new design is placed parallel to the stiff sailcloth. As illustrated for one typical strip in Figure 4, the sailcloth is slack at low loads, giving that portion of the pulling sheet the flexibility of the rubber strip, but tightens to take up the load as the capacity of the rubber is reached causing an inherent stiffness jump. The complete pulling sheet consists of a series of such elements. The reinforced sailcloth is continuous through all of these elements but glued to each with sufficient slack to allow a predetermined stretch of each element. Each stretching rubber element is thicker (and therefore stiffer) than the preceding element in the series. Thus, as the load applied to the

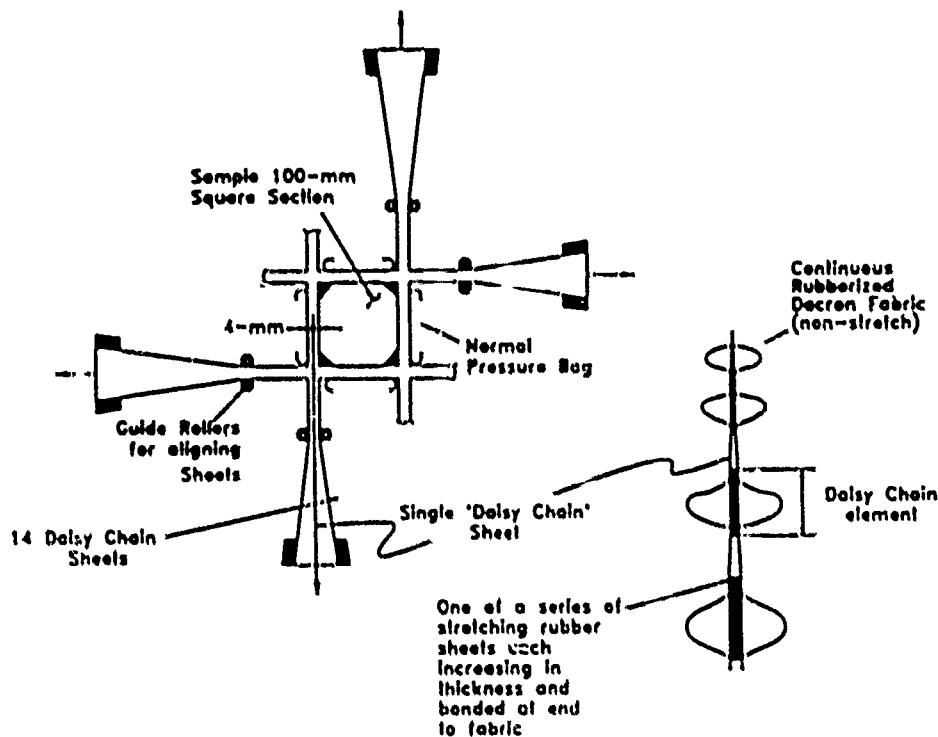


Figure 4: Principles of new wide-stress-range shear sheets

pulling strip increases, its stiffness increases accordingly providing optimal stress application at the specimen face for the full range of stress application. As an added benefit of this design, stress hysteretic effects are not produced during cyclic loading because the stretching elements are no longer subjected to normal pressures.

17. To accommodate shear-stress reversals four opposing pairs of daisy-chain shear sheets are used as shown in Figure 4. In Figure 5 the sailcloth strips are shown attached to the thin rubber sleeve that bonds to the specimen membrane. A complete set of strips is shown in Figure 6 interlaced as they are when placed in the apparatus for testing. Data obtained using daisy-chain sheets at UCL are compared with data from the original DSC in Figure 7.

18. The load is applied to the daisy-chain sheets through a clamp which is illustrated in Figure 8. The thickness of the shear sheets bundled at the clamp is determined by the number of rubber strips required to support the applied load. The load capacity of each strip is controlled by the amount of stretch permitted. Therefore, the thickness of the shear-sheet bundle at the clamp is determined by the required load capacity and the permissible stretch in the final unit<sup>1</sup>. The capacity of the daisy-chain links was limited to a maximum applied shear stress of 400 kPa to keep the thickness of the shear sheets at the clamp reasonable. Even with this limit on maximum shear stress, the permissible stretch of the final link in the chain had to be increased to 150 percent

<sup>1</sup>The final unit must remain flexible at the higher load levels.



Figure 5: Sailcloth pulling strips attached to the rubber sleeve

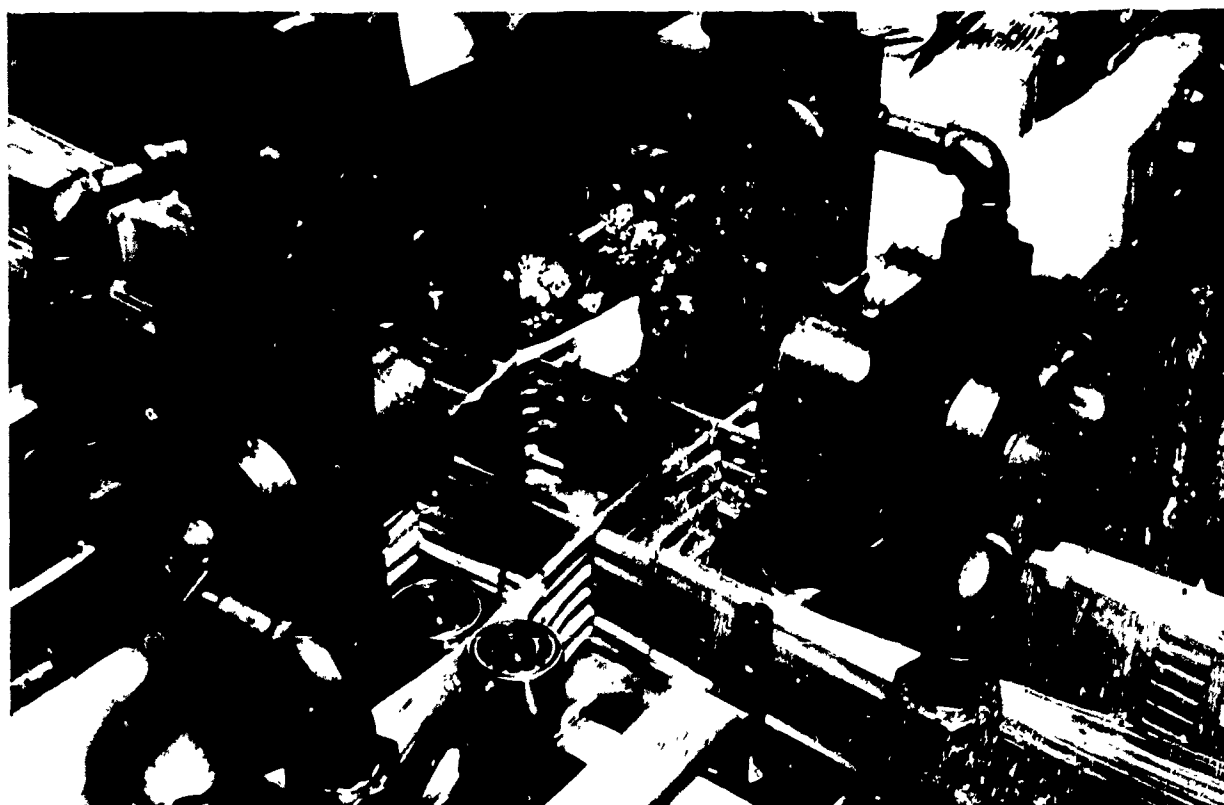


Figure 6: Pulling strips of the shear sheets interlaced in the apparatus

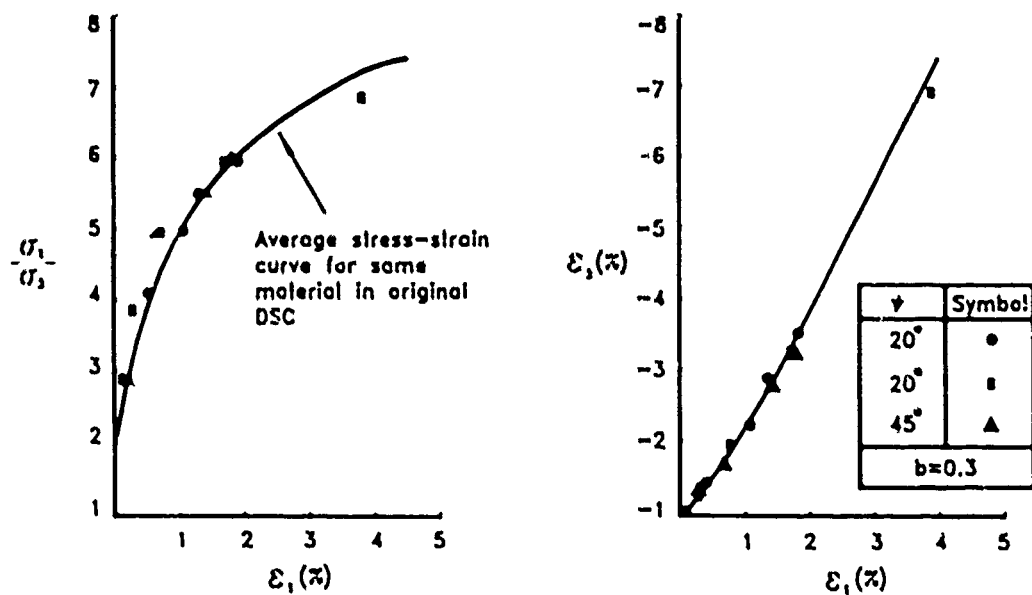


Figure 7: Comparison of stress-strain data for dense Leighton Buzzard sand from the original DSC and the new daisy-chain DSC

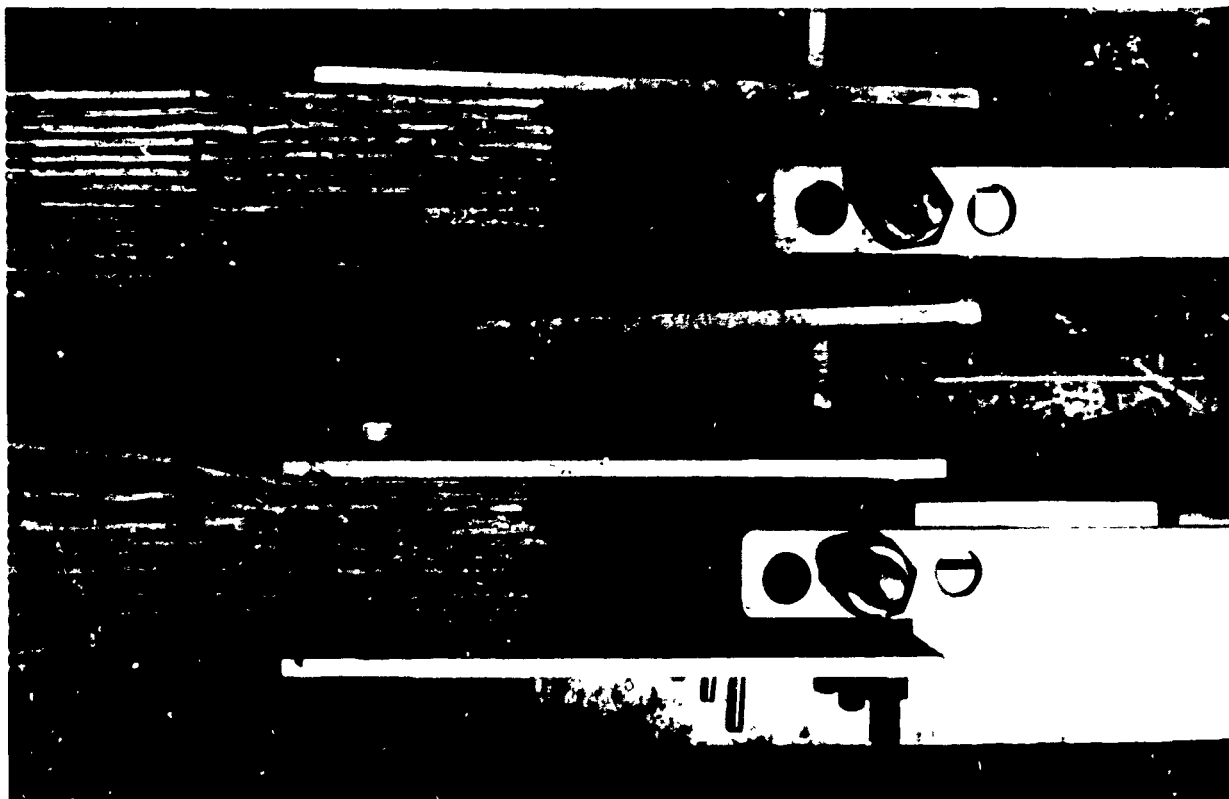


Figure 8: Clamps holding shear sheets

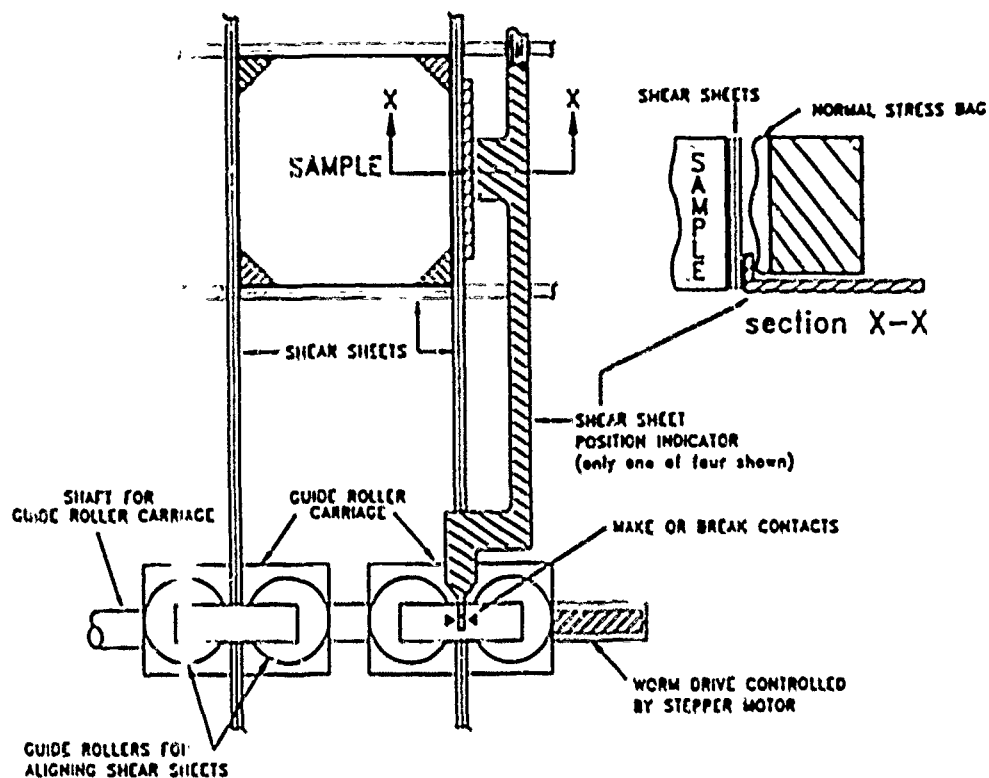


Figure 9: Shear-sheet positioning system

change in length (versus 100 percent in the other units) to achieve the desired combination of capacity, bundle thickness, and flexibility.

### Alignment of Shear Sheets

19. The shear-sheet alignment system is designed to keep the pulling direction parallel to the specimen face, thereby maintaining the shear and normal force distributions uniform. This alignment is especially critical at the specimen corners where the contact between the normal-pressure bag and specimen can be lost if the sheets become misaligned. The reorientation of the shear sheets is accomplished by guide rollers located near the specimen. This arrangement is shown in Figure 4. The use of guide rollers is a significant simplifying improvement to the original apparatus which maintained alignment by moving the complete pneumatic loading system to accommodate deformation.

20. Shear-sheet alignment is controlled through a rigid brass shear-sheet position indicator which sits between the shear sheets and normal-pressure bag, as shown in Figure 9. The indicator is held in place and supported by friction between the shear sheets and the normal-pressure bag. The indicator follows the face of the specimen and is free to translate and/or rotate as the specimen face moves. Section X-X in Figure 9 shows the position indicator located between the

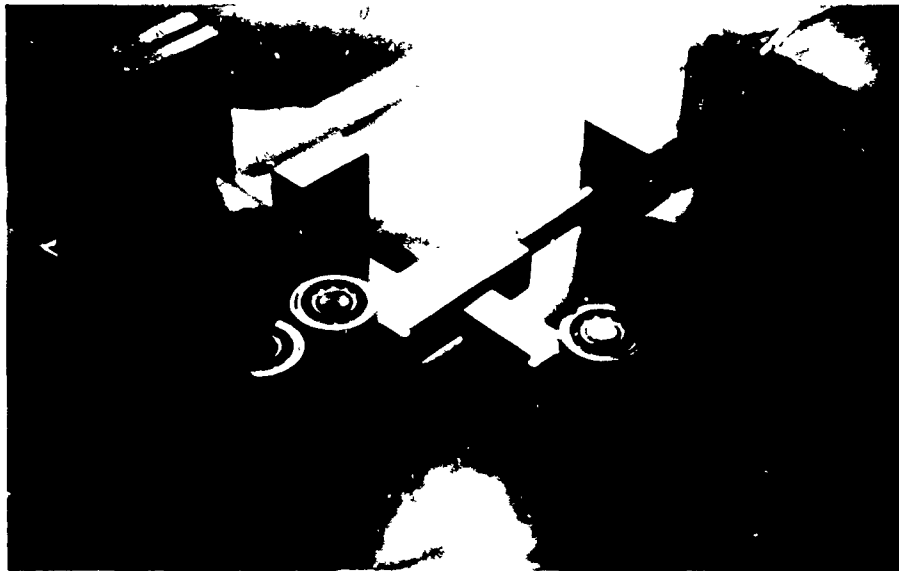


Figure 10: Shear-sheet guide-roller assembly

normal-pressure bag and the shear sheets. The ends of each indicator lie between make-or-break electrical contacts which monitor movement and thereby control the stepping motors which drive the shear-sheet guide rollers. When the indicator moves out of alignment (approximately 0.1 deg), contact is made and the stepping motors are activated to push the rollers in the direction that will again break contact. Thus, the rollers are maintained in line with the rigid position indicator thereby keeping the shear sheets parallel to the specimen face. Permanently maintained gaps above and below the ends of the normal-pressure backing plates ensure that the indicator is not restrained in the horizontal plane. The shear-sheet guide-roller assembly is shown in Figure 10. Figure 11 shows the maximum range of specimen deformations which must be accommodated by the alignment system.

### Alignment of Normal-Pressure Bags

21. Figure 12 illustrates the alignment control for the normal-pressure bags. Figure 13 shows the relevant parts of the normal-pressure system. Each of the four normal-pressure systems is comprised of a pneumatic loader, backing plate, and pressure bag. The pneumatic loader consists of two balanced Bellofram cylinders that apply parallel loads through roller bushings to the rear of the backing plate. The backing plate is free to translate forward and backward,

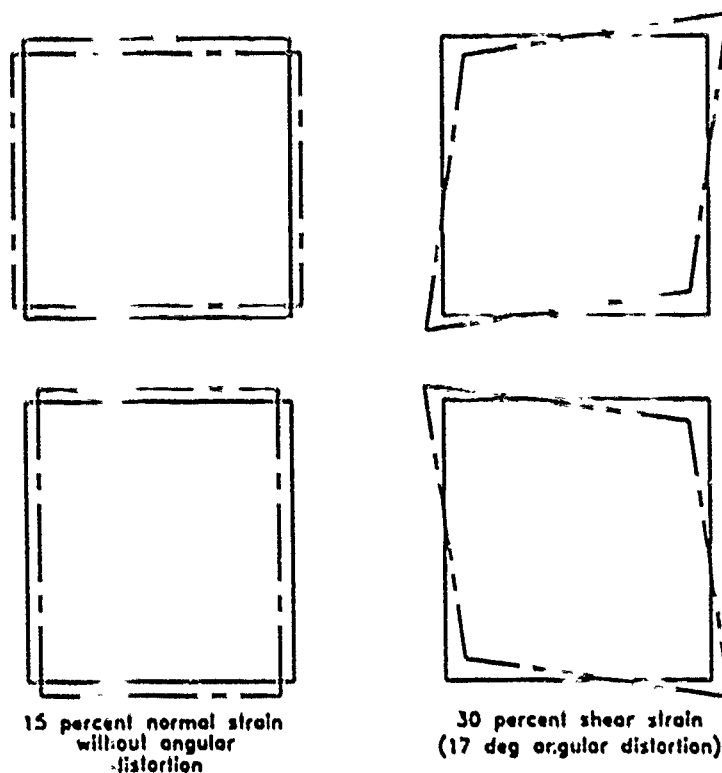


Figure 11: Range of specimen deformations

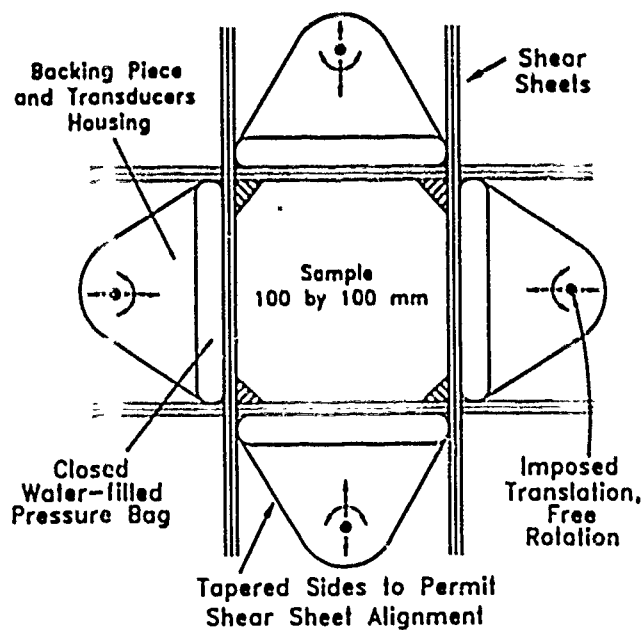


Figure 12: The application of normal stress

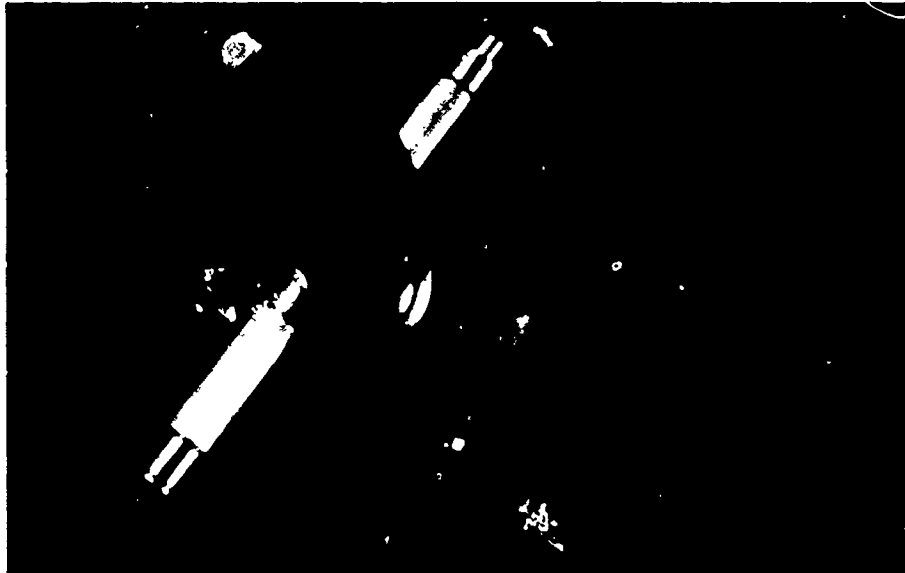


Figure 13. Normal-pressure bag assembly showing bag, backing plate, and roller bearing attachments

apply normal loads, and rotate on the roller bushings to allow self-alignment with the face of the specimen. Uniform contact pressure is applied to the specimen through a constant-volume reinforced pressure bag that is bonded to the backing plate. The bag is filled with water to maintain the constant volume condition under pressure. The rotational freedom of the backing plate allows the face of the pressure bag to follow the specimen, thereby maintaining uniform pressure at the specimen-bag interface.

### Strain Measurement

22. Strains must be determined from deformations obtained through photogrammetric techniques. Photographic or video images can be obtained through the glass window in the top plate to determine deformations of a grid drawn on the specimen's top membrane. Alternatively, a provision has been made for placing an X-ray film cassette just below the baseplate for taking high-quality radiographs. Displacement measurements of markers placed in a central horizontal plane of a specimen allow strain distributions to be computed. Wong and Arthur (1985a) describe the radiograph technique and compare strain data at the end-plane and mid-plane of samples tested in the original DSC.



Figure 14: Flexible drumhead pressure bag used to apply the  $\sigma_2$  stress

23. All DSCs are inherently load controlled. Stress control can be obtained approximately but strain control requires a feedback system in which deformations are measured and pressures adjusted to maintain the desired path. A feedback system requires an automated measurement system for deformations. Neither photography nor radiography is suited for such an automated system. The automatic alignment system for the shear sheets should in theory be able to provide automatic boundary strain measurements. Although this potential may eventually be achieved, it has not been achieved as yet.

24. Apart from the practical limitations of current strain measurement systems for the DSC, developmental tests using the original DSC design suggest that there may always be difficulties in resolving accurate strains less than 0.5 percent using existing photogrammetric methods. Alternative deformation measurement systems remain an important area for developmental research for this DSC design.

### Stress Path Control

25. The applied boundary stresses acting in the central horizontal plane are  $\sigma_a$ ,  $\sigma_b$ ,  $\pm\tau_a$ , and  $\pm\tau_b$ . In addition, the intermediate principal stress  $\sigma_2$  may be controlled by a "drumhead" pressure bag (Figure 14) to within values of  $b$  required to maintain nearly plane-strain condi-

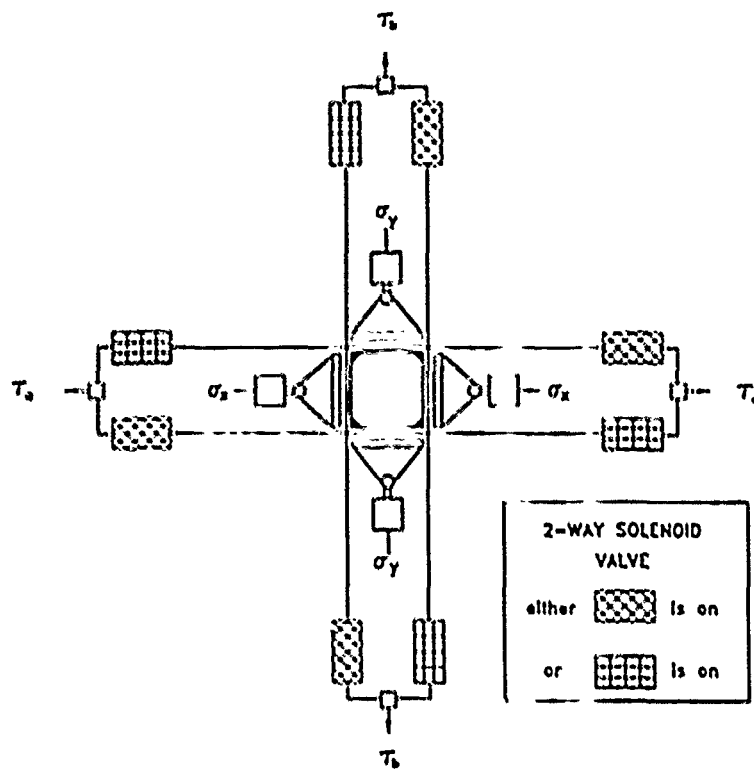
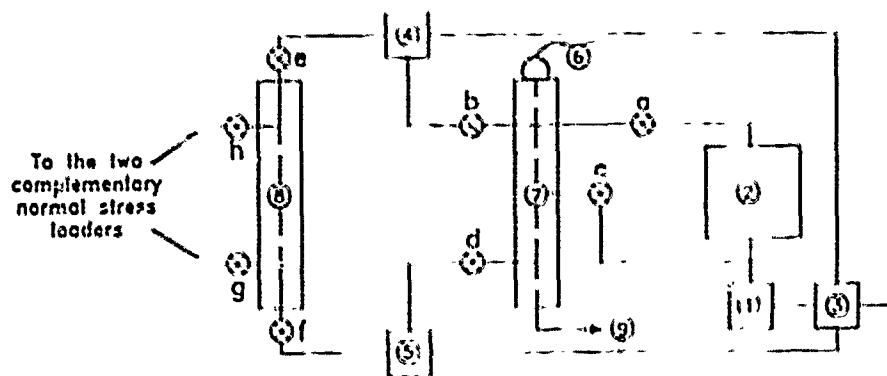


Figure 15: General layout of air pressure flow and control

tions. All of these components are controlled independently, either manually by five pneumatic regulators, or automatically by five stepping motors that control motorized pneumatic regulators (Figure 15). The directions of  $\tau_a$  and  $\tau_b$  are reversed by simple solenoid valves which can be operated either manually or automatically from a computer. A sensitive system for detecting very small pore water pressure changes in the specimens is used for undrained testing by the null method.

26. Loads are applied through five pneumatic control boards. Four identical pneumatic control boards supply regulated air pressure to Bellofram pneumatic loaders (Figure 15) that apply the  $\sigma_a$ ,  $\sigma_b$ ,  $\tau_a$ , and  $\tau_b$  stresses. The fifth board is used to regulate the pressure to the single drumhead pressure bag that applies the  $\sigma_2$  stress. Air pressure for all boards is supplied from a distribution manifold that receives regulated air pressure from a central supply.

27. The layout of a typical pneumatic control board is shown in Figure 16. Regulated supply air pressure is distributed through primary manifold ③ to regulator ① and volume booster relays ④ and ⑤. Manifold ⑦ distributes the pneumatic signal to the volume boosters. For manual control, manifold ⑦ is supplied by regulator ①, which has a range of 14 to 1,020 kPa. For automatic control, manifold ⑦ is supplied by Norgren precision pneumatic converter ②, which has a standard range of 14 to 830 kPa and is, in turn, supplied by regulator ①. The choice of manual or automatic control is made through the disposition of valves a and c. For



- |   |  |
|---|--|
| (1) Manual Regulator<br>(Fairchild model 10)                | (5) 1:3 Volume Booster<br>(Fairchild model 20)               |
| (2) Motorized Regulator<br>(Norgren pneumatic<br>converter) | (6) 1.5-MPa Druck Pressure<br>Transducer                     |
| (5) Primary Air Supply<br>Distribution Manifold             | (7) } Secondary Air Pressure<br>(8) } Distribution Manifolds |
| (4) 1:1 Volume Booster<br>(Fairchild model 20)              | (9) Link to other boards for<br>calibration purposes etc.    |

NOTE: Valves on a typical control board  
are of a 19-mm brass bull-type.

Figure 16: Schematic of a typical air pressure flow and control board

manual control, valve c is open and valve a is closed. For automatic control, valve a is open and valve c is closed.

28. The operating range of the pressure control board depends on which volume booster is used. Volume booster (4) maintains the standard range set by either the manual control regulator (1) or pneumatic converter (2). Volume booster (5) triples the standard range. The volume boosters also increase the bleeding capacity of the pressure system, thereby allowing faster response to pressure decreases. The signal pressure to the volume booster is measured in manifold (7) using a 1.52-MPa Druck pressure transducer (6). The pneumatic loaders are supplied by manifold (8) which is supplied by the appropriate volume booster, either through valves b and e or d and f. Valves g and h direct pressure to the pneumatic loaders either as a pair, as for a test, or individually, as for calibration.

29. The pneumatic converter consists of a regulator linked to a d-c stepping motor through a small gearbox. The converter is linearly precise through its entire range and is controlled by computer. Regulator (1) supplies the main air pressure to the pneumatic converter (2) and thus controls the converter's maximum output. The maximum input pressure for the pneumatic converter is 1,035 kPa.

30. Both computer and manual operation of the pneumatic converter are achieved through the stepping motor control box. The motor control box has five channels, one for each

pneumatic converter, which enables independent operation in any one of three modes (manual, jog, or auto). For setting up, the motorized regulator is operated manually from the motor control box. For manual operation, the auto/manual switch should be on manual, and the auto/jog switch in either position. In this mode either of the two direction buttons, when pressed, will continue to drive until the button is released or the valve spindle of the motorized regulator hits an electrical limit, stop.

31. In the jog mode the motor can be pulsed in single-step increments in either direction. It is also used for setting up the initial stresses in a test when precision control is needed. To operate the motorized regulator in the jog mode, the auto/manual switch should be in the auto position. When the jog button is depressed, the relevant stepping motor will be pulsed by a single step in the direction indicated by the jog switch.

32. For computer control of the motorized regulators, both switches should be on auto. The stepping motor can be pulsed in any direction with any number of pulses up to a maximum of 1,000 steps per command. One pulse of the stepping motor is approximately equal to a regulator output of 0.4 kPa; for each of the motorized regulators this relationship has to be determined precisely. The calibration consists of pulsing the regulator by a specified number of steps noting the pressure difference; the average change in pressure produced by a single step is calculated.

33. Prior to operation of the pneumatic converter it must be manually operated to its lower electrical stop using either the jog or manual mode. For this operation, valves b, c, and d are closed and valve a is opened to permit measurement of the lower-limit signal pressure by transducer ⑥. At the lower electrical stop the transducer should read the minimum signal pressure.

## Undrained Testing

34. The null method is used to test specimens in the undrained condition. In the null method the volume is kept nearly constant by adjusting the mean stress to offset any detected tendency to change volume. The tendency to change volume is detected either by a high-resolution volume change indicator or a pore water pressure transducer. The null method maintains the specimen's pore water pressure at zero, thus making the applied stresses effective stresses. This method has been adopted for the new prototype DSC because any internal pore water pressure would cause expansion or contraction along the edges of the specimen's membrane, negating the constant volume condition.

35. The implementation of the null method in the present design is based on measuring the pore pressure. Either an internal pore water pressure transducer or a hard external link to an

external transducer is used to monitor any small incremental change in the pore water pressure. When a change is either observed or sensed, all normal stresses are adjusted uniformly to return the pore water pressure to zero. Adjusting the mean total stress in this manner maintains  $b$  constant. In the original DSC at the UCL this adjustment is automated. A study employing the conventional and null methods for undrained shear testing of triaxial specimens at UCL showed no difference in results. Recently, this fact was confirmed at the Norwegian Geotechnical Institute by a study of undrained data from simple shear tests (Dyvik et al. 1987).

### Summary of Specified Apparatus Capabilities

36. The capabilities of the apparatus are:

- a. A full range of soils including loose and dense sands, and normally and overconsolidated clays, can be tested.
- b. Undisturbed specimens as trimmed from 125-mm tubes or larger can be accommodated.
- c. Any stress history in a plane can be reproduced, including principal stress axes rotation through any angle, up to and in excess of 360 deg.
- d. Self-aligning shear sheets can apply surface shear stresses up to 400 kPa.
- e. Self-aligning normal-pressure bags can apply normal stresses up to 700 kPa.
- f. Soils can be tested in the undrained condition (constant volume).
- g. Cyclic boundary shear stresses can be applied with nominal hysteresis.
- h. The  $\sigma_2$  value can be controlled up to the limitation that  $\epsilon_2 < 1.0$  percent.
- i. Strains and strain distributions can be determined using either photography or radiography.
- j. Monotonic and cyclic stress histories can be applied automatically.

## PART III: EXPERIMENTAL TECHNIQUES

### Normal-Pressure Bag Filling Procedure

37. The volume of water in the normal-pressure bags is important because an incorrect stress distribution will result from overfilling or underfilling. If overfilled, the bag will "punch" into the specimen causing stress concentrations in the central region of the bag (Figure 17a). Likewise, if underfilled, stress concentrations will exist at the boundaries (Figure 17b). The ideal situation is a uniform stress distribution across the face of the normal-pressure bag (Figure 17c).

38. The correct volume of water in the bag is achieved by the following procedure. The normal-pressure bag assembly is placed on its back, and a lucite plate with the same dimensions as a specimen face (75 by 100 mm) is positioned on top. A 11.335-kg (25-lb) deadweight is placed centrally on top of the plate; an increase in stress is indicated by the connected pressure transducer. Given the pressure in the bag and applied load, the effective loaded area of the normal-pressure bag can be determined as  $\text{effective area} = \text{applied load} / \text{measured stress}$ . This procedure is carried out for different volumes of water until the correct effective area is obtained (Figure 18). When the proper volume is obtained, the bag is isolated by closing the valve at the base of the assembly. The above procedure is repeated for all four bags.

### Calibration of Shear Sheets

39. Calibration of the shear sheets provides assurance that the pressure applied to the pneumatic shear loaders is approximately linearly related to the shear stress applied to the specimen faces. If no frictional losses exist, the shear stress is proportional to the pressure applied to the shear loader; the proportionality constant is equal to the ratio of the area of the specimen face to the effective area of the shear cylinder. The relationship between the ideal and actual calibrations has been investigated by Rodriguez (1977) and Bekenstein (1980). Because frictional losses occur in the system there is a deviation from proportionality as is evident from the calibration data shown in Figure 19. It is seen from the calibration that not only is there a deviation from proportionality; there is also a distinct hysteresis in the loading and unloading of the shear sheets. Experience has shown that the consistency and repeatability of the lubrication procedure in reducing frictional losses causes little variation in the actual calibration with time. Therefore, only an occasional calibration check is required.

40. The calibration procedure is begun by setting up a specimen using the specimen

### Stress Distribution



### Bag Inflation

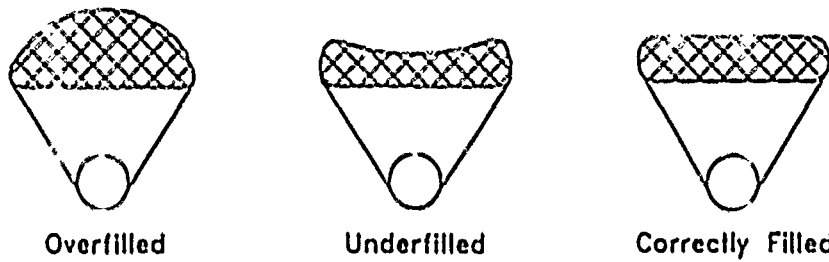


Figure 17: Effects of different volumes of water in a normal-pressure bag

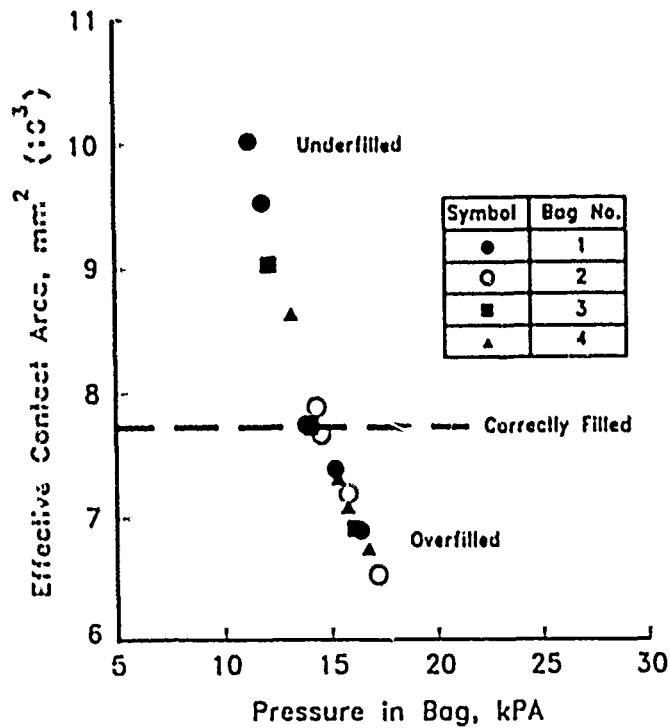


Figure 18: Calibration for correct filling of a normal-pressure bag

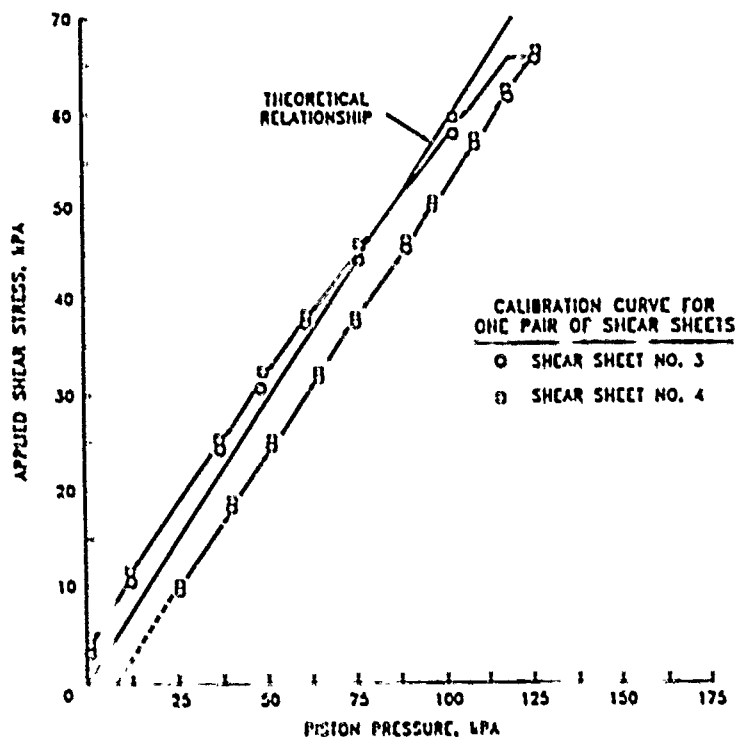


Figure 19: Calibration curve for one pair of shear sheets

preparation and setup procedures described below. Either a sand specimen under a high vacuum or a dummy specimen covered with a latex specimen membrane that has been glued to the dummy specimen can be used (the sand specimen is easier to fabricate and use). The major requirement is that the specimen act as a rigid block. Hereafter, both the sand and dummy specimens will be referred to simply as specimens for calibration purposes.

41. The first step in the calibration is to apply an equal normal stress to all specimen faces. The magnitude of this stress is immaterial as long as it is within a limited range (Bekenstein 1980). The pressure in the  $\sigma_2$  bag should be sufficient to maintain the specimen slightly above the baseplate of the DSC. The normal stresses are increased equally and *simultaneously* by using a common regulator. Pressure is slowly increased while the stress in the normal-pressure bags is monitored until the calibration stress is reached.

42. Once the calibration stress is reached, the normal stress loaders which act on opposing sides of the specimen are reconfigured so that they no longer operate in unison. Instead, adjacent loaders are operated as pairs. This arrangement is illustrated in Figure 20. The shear loaders are likewise reconfigured such that shear stress is applied to one pair of adjacent faces. The pressure lines to the pair of normal-pressure bags acting on the faces to be sheared are isolated so that these normal-pressure bags act as stress sensors. The pneumatic loaders of the isolated pair are restrained from movement by inserting tuning-fork-shaped spacers between the backing plates

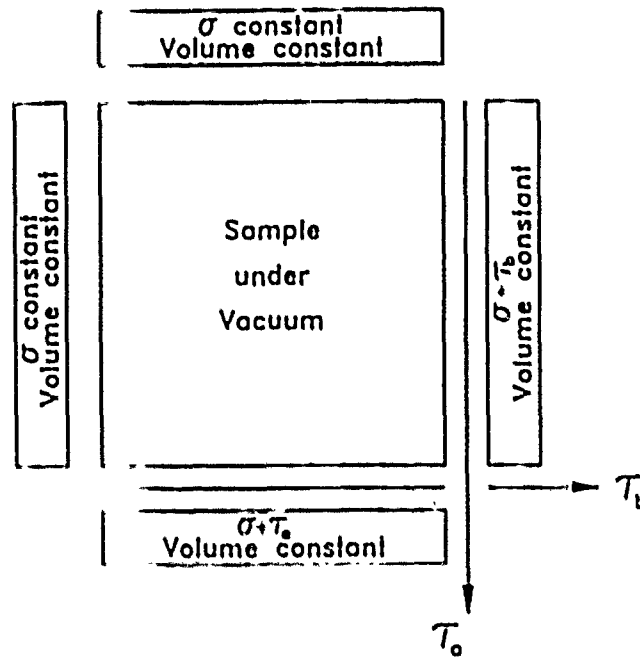


Figure 20: Experimental arrangement for shear-sheet calibration

and the pressure cylinders. The other pair are left open to maintain a constant stress against the specimen. The shear stresses may now be applied through one adjacent pair of shear loaders. When the shear stresses are applied, the pressure in the isolated pair will increase by an amount equal to the applied shear. The procedure may now be repeated for the other six shear sheets. Prior to each calibration, all normal stresses are relieved to zero and the specimen is centered and realigned on the baseplate.

43. The hysteresis shown in Figure 19 suggests that a pressure of approximately 10 kPa is needed in the pneumatic shear loader to initiate specimen movement into the isolated pressure bags. In effect, this measured frictional loss includes not only friction in the shear loader but also friction in the interfaces between the specimen and surrounding normal-pressure bags. It should be noted that the frictional losses include viscous forces derived from the lubricating grease and thus may be time dependant. The viscous forces are evident in tests at failure as it is generally observed that a specimen may remain stationary under a constant load for some minutes before large deformations attended with failure actually occur.

## Specimen Preparation

44. Methods of specimen preparation will differ in accordance with the material being tested and the purpose of the test. An example of a basic procedure for reconstituting sand specimens for tests described in this report is shown in Figure 21. Techniques for preparing trimmed clay specimens for testing are described in detail by Germaine (1982) and will not be dealt with in this report.

45. Before a specimen can be reconstituted the latex membrane and sealing sheet are fabricated in accordance with the instructions in Appendix A. In addition, because the apparatus has no mechanical or electrical method of measuring strains, a fine-lined grid must be drawn on the sealing sheet (step ① of Figure 21) prior to sealing the specimen in the membrane. From the grid the magnitude and uniformity of the induced strains can be determined. Experience with the apparatus has shown that strains observed on the grid surface are replicated in that plane through the depth of the specimen.

46. The following procedure can be used to prepare the specimen membrane and mold for reconstitution of sand specimens. The specimen mold is cleaned and assembled using vacuum grease to seal all joints. The membrane will be held in place against the mold using a vacuum. To insure the membrane will conform completely to the mold shape, a stiff porous fabric is placed on all interior surfaces of the mold to distribute the vacuum. The top edge of the mold is coated with vacuum grease to seal the area to be evacuated. The membrane is placed in the mold with its top edges extending over the exterior sides of the mold and held in place with one or more rubber band(s). A partial vacuum is then applied to suck the membrane against the mold. The membrane is smoothed into a wrinkle-free prismatic shape using either a glass rod or small brush before the full vacuum is applied.

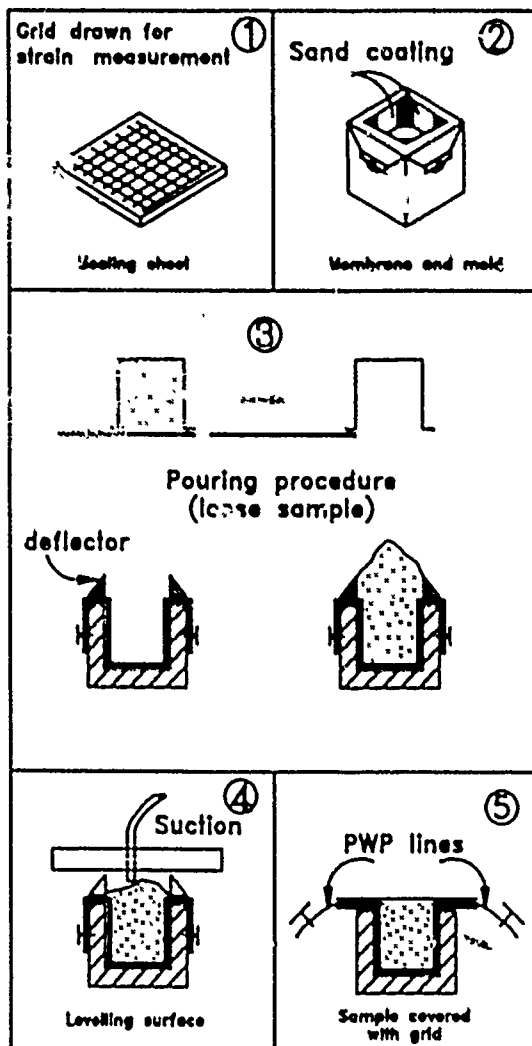
47. Two aluminum strips (2.0- by 9.5-cm)<sup>1</sup> are glued to the inside surfaces of each corner using Evostik 9162<sup>2</sup> (see step ② of Figure 21). The space between the two aluminum strips is filled or partially filled with a sand and latex glue matrix forming a triangular prism in each corner of the specimen. It has been found that these strengthened corners aid in preventing progressive failure from the corners, yet deform to follow the change in shape of the specimens during loading (Figure 11).

48. The transfer of shear stresses to the specimen requires that a coating of sand particles similar to those that constitute the specimen be glued on the inside surfaces of the membrane.

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<sup>1</sup>Aluminum corner strips are used because it has been found impossible to maintain the correct boundary stresses in the corners of the specimen. Shear stresses applied close to a specimen's edge cause progressive failure of the whole specimen if these plates are not used.

<sup>2</sup>A latex adhesive manufactured by Evode Ltd., Stafford, United Kingdom.



- ① Sealing sheet placed on glass plate and grid drawn with India ink.
- ② Sample membrane placed in mold stiffing corners constructed, and inside of membrane coated with sand.
- ③ Pluviation of sand into the sample mold.
- ④ Top surface of sample leveled using a suction technique.
- ⑤ Pore Water Pressure (PWP) lines placed in sample corners and sample sealed with sealing sheet.

Figure 21: Preparation of a dry sand specimen

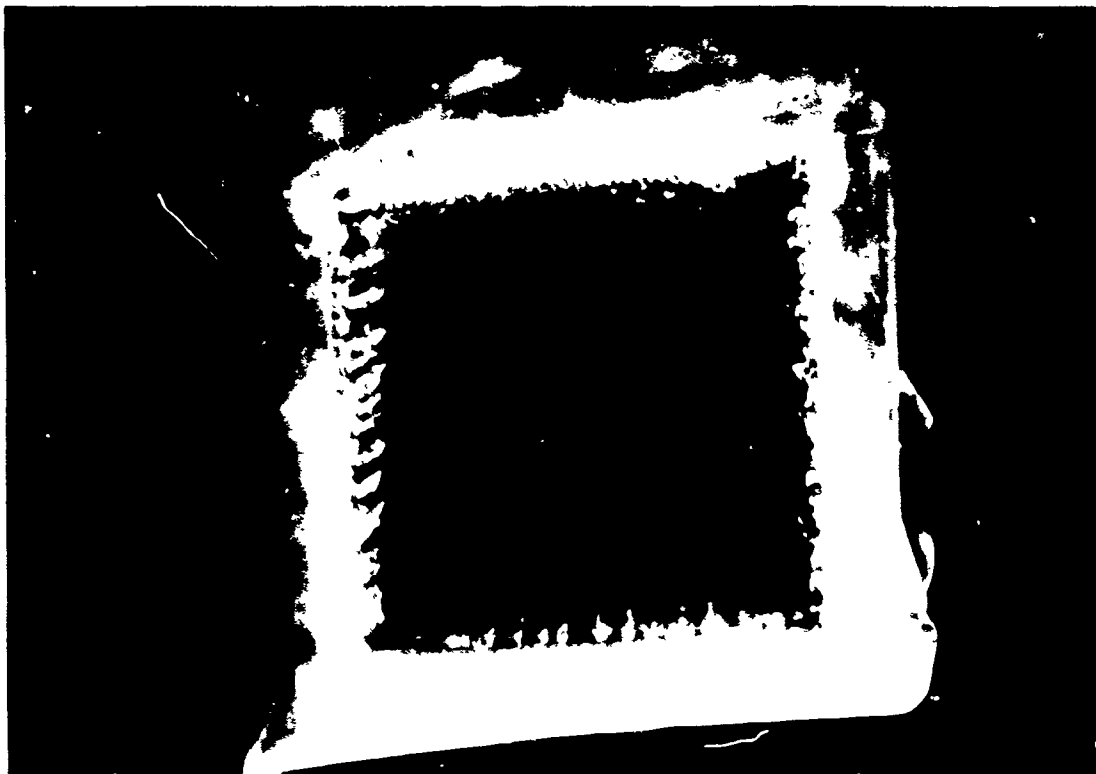


Figure 22: Sand "teeth" glued to inside of specimen membrane

Treating one face of the membrane at a time, the mold is positioned so that the surface to be coated is horizontal. Evostik adhesive is spread on the face generously before pouring particles of sand over the surface. Using a rod, the particles are spread evenly over the face while the grains are pushed into the adhesive. The excess sand particles are poured off before repeating the process on the next side. Alternatively, a shaping comb may be drawn upwards through the sand grains and Evostik glue to form sand "teeth" on the inside of the membrane (Figure 22). The grooves should be spaced approximately 0.5 cm apart with their position corresponding to the location of the vertical nonreinforced strips in the shear sleeve when it is brought into contact with the membrane. After the four sides are coated, the specimen mold is turned open side up and the glued sand boundaries and corners are allowed to cure for at least 12 hr.

49. Before pluviating a specimen, a deflector is placed on the specimen mold to maintain a uniform density from the center of the specimen to the outer edges (step ③ of Figure 21). The rate and height of deposition in air governs the density of the finished specimen. Thus both variables should be kept constant during deposition. The lower the rate of deposition the higher the density, and vice versa. In particular, a horizontal sand surface should be maintained to help ensure a uniform density. After the mold has been slightly overfilled, excess particles are carefully sucked up with a vacuum tube that is held at a fixed height (step ④ of Figure 21); the height of the tube is gradually reduced until only excess particles are being removed. Care is taken not

to touch the particles with the tube. After the specimen has been leveled off with the vacuum, the deflector is removed and a small brush is used to remove any particles that remain on the membrane that covers the top horizontal rim of the mold.

50. Two pore water pressure line assemblies are prepared before the sealing sheet can be attached to the specimen. Each line consists of a 4-mm polyethylene tubing covered at the specimen end by a 40-mm length of thin rubber tubing (see Appendix A). The thin rubber tubing has a very small roll of polyester material inserted into it to prevent specimen particles from blocking the pore water pressure lines. The mold contains grooves on opposing corners to accommodate these pore water pressure lines.

51. To obtain an airtight and watertight seal between the sealing sheet, pore water pressure lines, and specimen membrane, all rubber surfaces are cleaned with acetone and covered with adhesive (Evostik 9162). The adhesive is applied to all sealing surfaces and then let stand until the adhesive becomes transparent. The thin rubber tubes of the pore water pressure line assemblies are first laid in grooves at diagonal corners such that only the section of the thin rubber tubes that contains the polyester material extends into the specimen particles. The other ends of the polyethylene tubing are supported to avoid disturbance of the specimen and membrane during placement of the sealing sheet. The sealing sheet is placed on top of the specimen and pressure is applied around the rim of the mold to ensure sealing of all rubber surfaces (step ⑤ of Figure 21). After the top sealing sheet is glued in place, a small vacuum (35.0 kPa) is applied to the specimen's interior through the pore water pressure lines.

52. After the vacuum is applied to the interior of the specimen, finger pressure is applied around the polyethylene tubing to ensure no leakage in that area. The vacuum should always be less than the normal stress which is applied during the test to avoid permanent changes in specimen stiffness. The mold is dismantled and the specimen is slid off the mold baseplate onto a clean surface. After dismantling the mold, the specimen membrane is checked for leaks. If any are found, either a glass or metal rod is used to apply adhesive to the area in question. Finally, the top lip of the specimen (the interface between the specimen membrane and the sealing sheet) is trimmed such that approximately a 6-mm lip of material remains. If there is interference by the lip it can be folded inward over the specimen for gluing. Further details are given in Chapter 4 of Wong (1985). The specimen is now ready to be placed in the apparatus for testing.

53. Although saturated DSC sand specimens have been prepared at UCL for testing in a version of the original DSC, the details of specimen preparation are not directly appropriate to the new DSC. One technique that could be used is the replacement of air in the specimen with carbon dioxide before allowing *de-aired* water to slowly percolate through the dry specimen. With this saturation method it would be necessary to have a pore water pressure line attached

at the base of the specimen. In addition, it may be necessary to have additional exit lines from the upper corners of the specimen. These lines must be sufficiently rigid to avoid volume change during the undrained, constant volume testing. There also must be an effective means of sealing all pore water pressure lines.

## Specimen Setup

### Lubrication of shear sheets

54. Lubrication is a critical concern in preparing the shear sheets for either calibration or testing. The surface of the fabric strips and the back of the nonreinforced facing sheets are the only lubricated areas of the shear sheets. All other parts must remain grease free. Particular care must be used to avoid getting grease on the surface of the shear sleeve that bonds to the specimen membrane. If any grease does get on either surface an effective degreasing agent is trichlorethylene.

55. The lubricant is a mixture of Dow Corning Molykote silicon grease with 20 percent, by weight, PTFE powder. This mixture was found to be suitable for the stress range of this equipment (Arthur and Dalili 1979). It is probable that quite a range of silicon greases would perform adequately with the PTFE additive.

### Assembly for testing

56. The  $\sigma_2$  bag must be cleaned and lubricated before the specimen is placed in the apparatus. The shear-sheet rollers are moved to their outer stops to allow access to the  $\sigma_2$  bag. The pressure in the  $\sigma_2$  bag is increased until the surface of the bag is slightly above the level of the baseplate. An even layer of grease is then applied over the entire  $\sigma_2$  bag. Two well-greased rubber sheets (120 by 120 by 0.4 mm) are centrally placed over the  $\sigma_2$  bag. All entrapped air bubbles between the rubber sheets and the  $\sigma_2$  bag are slowly worked out, using finger pressure, before the specimen is placed into the DSC.

57. After preparation of the  $\sigma_2$  bag, the inner surface of the shear sleeves and the vertical surfaces of the specimen membrane are degreased and made tacky with acetone to ensure proper bonding of the shear sleeve to the specimen membrane. Areas of the specimen membrane that correspond to the location of the internal aluminum corner strips are lightly greased. Greasing the corners of the membrane is an additional precaution to ensure that no shear force is applied to the specimen's corners.

58. The specimen (with grid facing up) is placed centrally onto the  $\sigma_2$  bag with the specimen sides parallel to the shear sheets. It is crucial to align the shear sheets in the center of each side before the shear sleeves are firmly pressed and bonded to the specimen sides; alignment cannot be corrected once any portion of the sheet is bonded. Care must be taken to ensure that no grease intrudes between the two surfaces as they are pressed together.

59. Once the shear sheets are bonded to the specimen, the bottom pair of shear-sheet position indicators are placed onto the back of the shear sheets. The four normal-pressure bags are greased and tentatively positioned facing the vertical faces of the specimen and shear sheets (Figure 12). The same greasing procedure used for the bottom  $\sigma_2$  bag is now used for the four normal-pressure bags except there is only a single rubber sheet (100 by 75 by 0.4 mm). The top pair of shear-sheet position indicators can now be positioned onto the back of the shear sheets and the normal-pressure bags placed in their final position against the shear sheets. Finally, pressure is applied to the  $\sigma_4$  and  $\sigma_1$  pneumatic loaders until the normal-pressure bags apply an even pressure over each of the specimen's vertical surfaces.

60. In preparation for top platen placement, the top of the sample is greased using the same procedure as for the  $\sigma_2$  bag. The top platen is placed on the gridded surface of the specimen and secured. Pressure is applied to all normal-pressure bags ( $\sigma_4, \sigma_1$ , and  $\sigma_2$ ) until the desired initial isotropic stress is obtained. As the pressure is increased in the normal-pressure bags the sample vacuum is released. The assembly procedure is now complete and the specimen is now ready for consolidation.

### Initial consolidation state

61. The stress state applied to a specimen after setup is isotropic with the mean stress equal to the sum of the applied vacuum and any initial pressure applied with the normal-pressure bags. The consolidation state prior to a shear test, however, may range from all normal stresses being equal (isotropic), to each normal stress being different (orthotropic), or in some cases to some combination of normal and shear stresses, the choice being dictated by the practical or research problem under investigation. In cases where stresses are the same it is advantageous to apply them using a common regulator. As for a conventional strength test, sufficient time must be allowed after application of the initial consolidation stress state to allow dissipation of excess pore pressure.

## Stress application

62. Application of stresses is performed sequentially rather than simultaneously. The order in which they are applied should be considered carefully, both in planning a loading sequence and in interpreting test results. For frictional materials yielding is induced under monotonic stress paths by increasing the shear-normal stress ratio; thus, a step carried out by increasing shear stress before normal stress is likely to produce more plastic strain than if the normal stress is increased first. For paths that are not monotonic the case is not as clear-cut. A recommended sequence is to always increase the normal stresses before the shear stresses, and to increase stresses sequentially from the lowest to the higher normal stress followed by the lower to the higher shear stress, etc. It is, of course, advantageous to keep the stress increments as small as possible. Clearly, automation of the loading sequence offers the advantage of using virtually infinitesimal increments.

63. Failure of the specimen is normally accompanied by large strains which require a rapid response by the operator to avoid damage to the apparatus. Upon failure, the electric power to the stepping motors that position the shear-sheet guide rollers is switched off. Next, the specimen is placed under a vacuum to maintain the final-failed shape for a post-test analysis. Finally, the main air supply valve is shut off to allow all pneumatically loaded components of the apparatus to relax simultaneously as the air pressure bleeds off.

## Shear correction

64. Computation of pressures for a planned stress path should account for specimen distortion. As the specimen distorts, boundary stresses are no longer orthogonal to each other. To simplify computations, it is advantageous to plan a stress path in terms of principal stresses and their directions so that a correction can be made for each increment (Rodriguez 1977). The relationships among the applied boundary stresses, specimen distortion angles, and internal stress state are derived from Mohr's circle relationships as illustrated in Figure 23. The boundary stresses can be computed from the following equations:

$$\sigma_a = \frac{1}{2}\sigma_3 [(R+1) + (R-1)\cos 2(\psi - \alpha)]$$

$$\sigma_b = \frac{1}{2}\sigma_3 [(R+1) + (R-1)\cos 2(\psi - \beta)]$$

$$\tau_a = \frac{1}{2}\sigma_3 (R-1)\sin 2(\psi - \alpha)$$

$$\tau_b = \frac{1}{2}\sigma_3 (R-1)\sin 2(\psi - \beta)$$

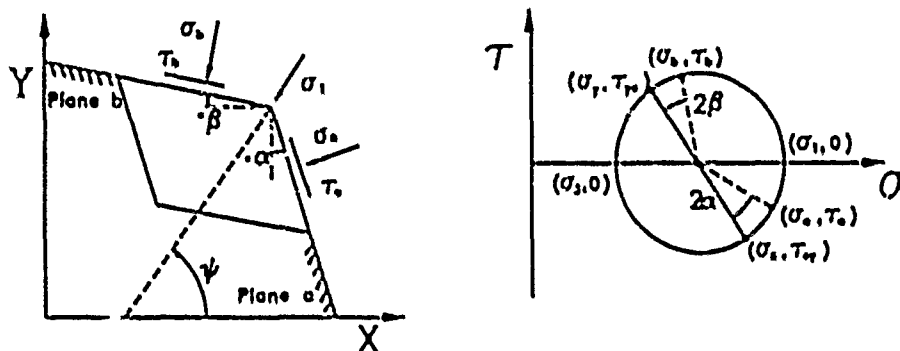


Figure 23: Correction of boundary stresses for changes in specimen geometry

Note that because the correction angles ( $\alpha$  and  $\beta$ ) are measures of the shear distortional strain, the relative error introduced by distortion is comparable to the shear strain. At the limits of the apparatus, illustrated in Figure 11, the error would be approximately 30 percent.

## PART IV: TESTED VERSUS DESIGN PERFORMANCE

### Stresses

65. The design limits for applied shear and normal stresses are 400 and 700 kPa, respectively. These limits are eight times those of the original DSC. Higher design limits could have been chosen, but practical design considerations made these limits adequate. While component tests have shown the chosen limits as attainable, operational caution has so far limited the attained boundary stresses to 215 kPa for shear stress and 560 kPa for normal stress.

### Strains

66. Figure 24 shows the distortion imposed on a Leighton Buzzard sand specimen. The maximum achievable homogeneous shear strain is in excess of 30 percent. Larger strains are possible when the full boundary shear stress is applied and lower strains are possible when no boundary shear stress is applied. This distinction is made due to the inability of the normal-pressure bags to follow the expansion of the specimen face beyond approximately 15 percent.

### Strain Rates and Cyclic Testing

67. All existing DSC designs have been operated with stress increments being applied very slowly. This apparatus has better response characteristics than previous designs allowing stress increments to be applied at faster rates (10-sec increments). However, experiments suggest that apparatus hysteretic effects will be reduced significantly at low strain rates. The effects of the viscosity of lubricating grease will be a factor in cyclic tests with a period of less than 20 sec.

### Validation Tests

68. The validation tests were designed to check the operation of the apparatus. The performance of each component was evaluated during its development as described previously in Part II. The validation tests assess the performance of the fully assembled DSC. All validation tests were carried out on dense Leighton Buzzard sand because it has an inflexible brittle behavior which shows up apparatus defects when applying the intended boundary conditions. This material was also appropriate because of the data that have been accumulated over time.

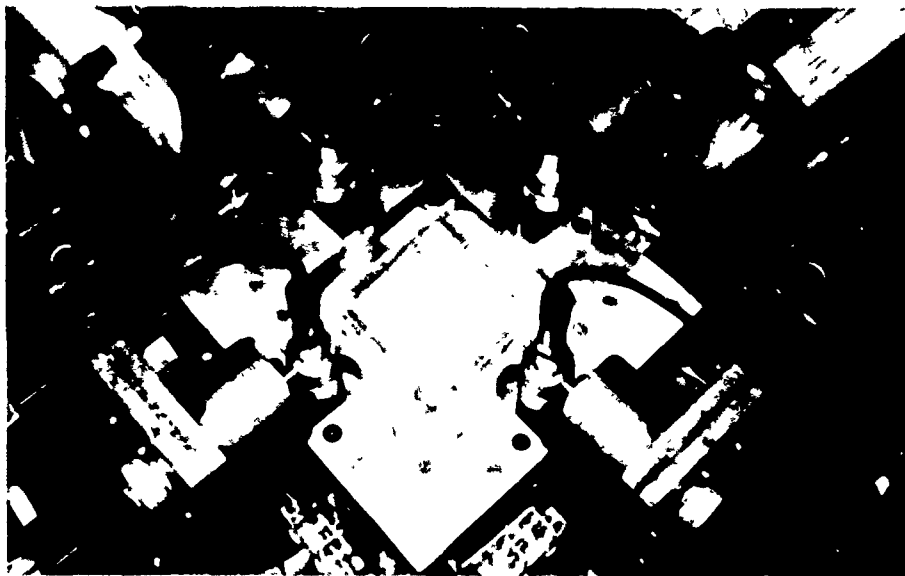


Figure 24: A deformed Leighton Buzzard sand specimen

69. Specimens were pluviated through air to a void ratio of 0.52. Pluviation was normal to the subsequent plane of strain so that all specimens were initially isotropic in the horizontal plane. All tests were performed under drained conditions at a mean normal stress of 50 kPa ( $\sigma_1 + \sigma_3 = 100$  kPa) and at  $b = 0.3$ . Five validation tests were performed as follows:

- a. Two tests were performed without principal stress rotation; one test was performed without shear sheets and one test included shear sheets. The purpose of these tests was to evaluate possible constraint effects on measured stress-strain behavior created by the shear sheets.
- b. Two additional tests were performed with applied shear but fixed principal axes (constant  $\psi$ ) to determine apparatus directional bias. Because the specimens were presumably isotropic in the horizontal plane, the stress-strain relationship, when expressed in terms of the principal stress and principal strain, should be the same for all tests.
- c. One test was performed with continuous rotation of principal axes to assess capabilities for applying fully controlled complex stress paths. Results for continuous rotation tests of the complexity achieved by the DSC are limited in other DSC-type equipment which has lower stress capacity; thus the validity of the results cannot be determined quantitatively. This test was evaluated primarily on the basis of maintaining specimen uniformity throughout large stress rotations.

In addition to the five validation tests, one cyclic test was carried out imitating one of the series reported by Wong and Arthur (1985b). The purpose of the cyclic test was to check out the

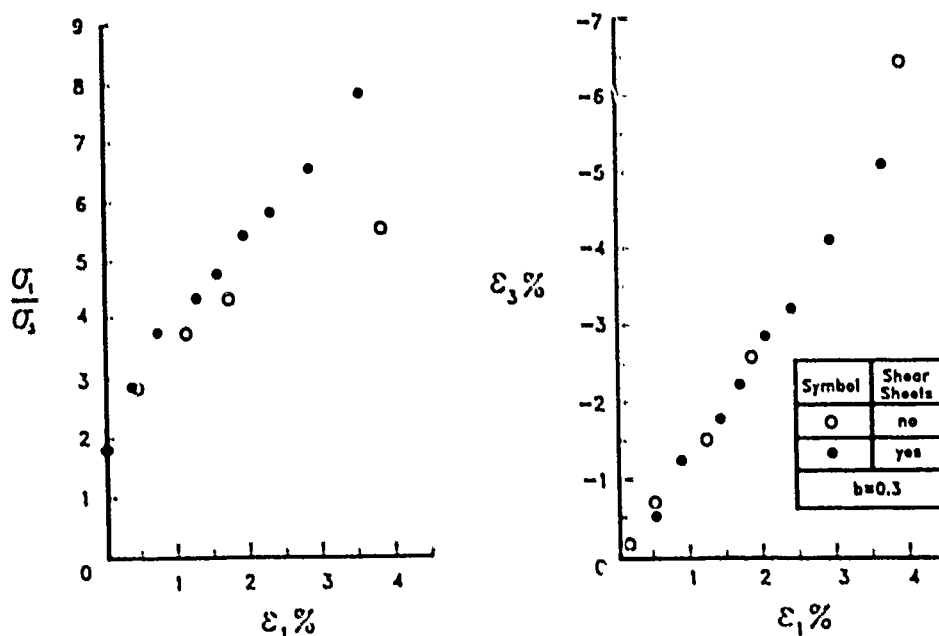


Figure 25: Restraining effect of shear sheets at a very low shear level

computer code used to automate the apparatus. The test results proved to be satisfactory and will not be reported here in detail.

### Constraint of shear sheets

70. The comparison of results with and without shear sheets (Figure 25) clearly shows that the shear sheets do provide constraint to the specimen. The effect is noticeable at approximately  $\epsilon_1 = 1$  percent. Beyond  $\epsilon_1 = 4$  percent the confinement effect is quite significant. Therefore at the low minor principal stress level reached at failure in these constant mean stress tests, the shear sheets prove to be an appreciable restraint. However, tests in the prototype DSC used to develop daisy-chain shear sheets show that this effect is diminished when the minor principal stress at failure is greater than 30 kPa. Evidently, the shear sheets provide a restraint that is related to strain but independent of stress. In contrast, the shear resistance of the specimen increases with increasing stress. Therefore, the relative contribution of the shear-sheet restraint to the total shear resistance is minimized at higher stress levels. Further development of experimental techniques may even eliminate this effect in the low minor principal stress range.

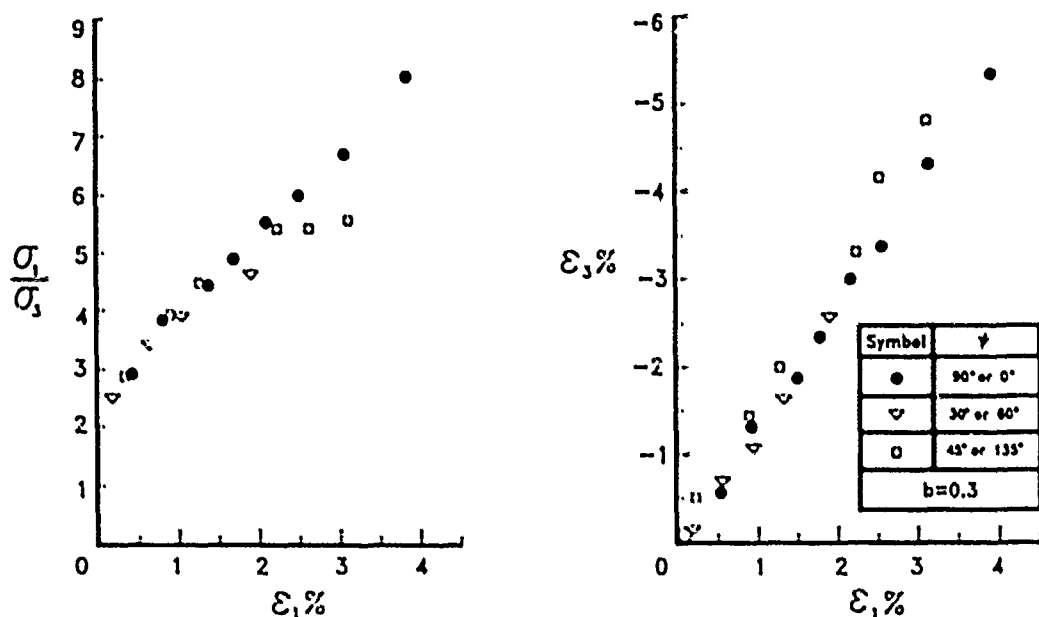


Figure 26: Monotonic test data for the same stress path but different applied boundary stresses

### Directional bias

71. The assessment of equipment bias is based on comparing the stress-strain response from three specimens sheared monotonically with respective values of  $\psi$  equal to 0, 30, and 45 deg. All tests performed with monotonically increasing shear stress, but constant  $\psi$  and mean stress, yield the same principal stress path and, in the absence of directional bias, should yield the same stress-strain data. Figure 26 shows that this condition is met up to failure. The test for  $\psi = 0$  deg appears to be somewhat more stable as it does not show a distinct failure. The test for  $\psi = 30$  deg is the least stable.

72. The bias in failure stress may be caused by the ease at which failure planes can form at the different principal axes orientations rather than a bias in the stress application. For example, as a general observation for tests on Leighton Buzzard sand in the DSC, failure planes form at an orientation of 71 deg from the  $\sigma_1$  plane. For this orientation, the failure plane would pass through one pair of opposing corners at  $\psi = 64$  deg. Presumably, such an alignment of the failure plane would be particularly unstable because the sliding plane does not intersect a normal-pressure bag and hence there is no resistance to sliding.

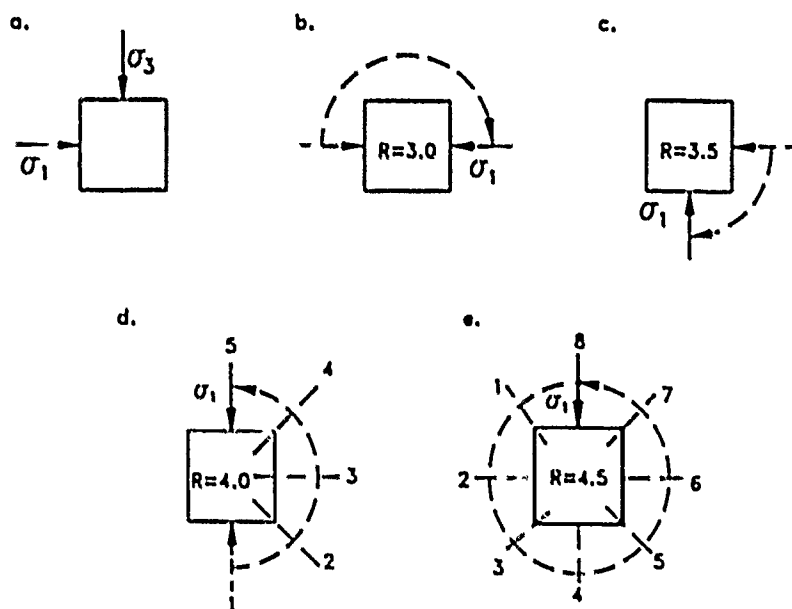


Figure 27: Loading sequence for test with continuous rotations

### Continuous rotation of principal axes

73. The loading sequence for the continuous rotation test is shown in Figure 27. From an initial hydrostatic state the specimen was loaded to  $R = 3$ , Figure 27a. A combination of shear and normal stresses was then applied to rotate the principal axes 180 deg clockwise while maintaining  $R$  constant, Figure 27b.  $R$  was then increased to 3.5, then maintained constant while rotating the principal axes an additional 90 deg clockwise, Figure 27c.  $R$  was increased to 4, then held constant while the principal axes were rotated 180 deg in the counter-clockwise direction, Figure 27d. Finally,  $R$  was increased to 4.5 and the principal axes were rotated, with constant  $R$ , a full 360 deg in the counter-clockwise direction, Figure 27e. The importance of this test lies in proving the capability of the apparatus. If quality results can be obtained even for such a severe rotation, the apparatus should be applicable for investigating any stress path of practical interest.

74. In terms of apparatus performance, the results were impressive. In particular, the specimen showed no signs of distortion even though the final 360-deg rotation produced incremental shear strains of up to 11 percent. The strains induced by the final 360-deg rotation are summarized in Figure 28. The shear strain is represented by the cumulative strain difference  $\epsilon_1 - \epsilon_3$  which is equivalent to the shear-strain path length, a quantity that by definition is always increasing. The volumetric strain is the cumulative volumetric change and may be either positive

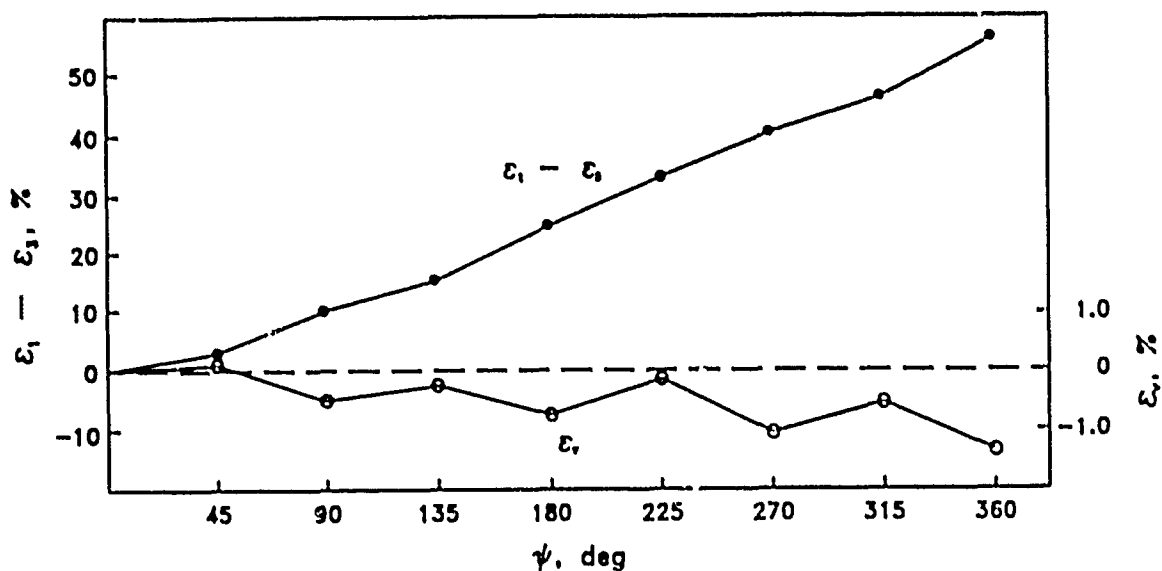


Figure 28: Cumulative shear and volumetric strains for final 360-deg rotation of continuous rotation test

or negative. Both the shear and volumetric strains have been plotted relative to the start of the 360-deg rotation.

75. During rotation the specimen became progressively softer as indicated by the increasing slope of the shear-strain versus  $\psi$  curve. This softening was accompanied by a small net volumetric expansion. The cyclic nature of the incremental volumetric strains is interesting and would not necessarily be expected because both the mean stress and principal stress ratio remain constant throughout the rotation. The limited data available suggest that this cycling between incremental contraction and extension is a result of sand behavior rather than being an artifact of the complex loading system. Volumetric cycling was observed in similar continuous-rotation tests conducted with the CU DSC (Sture, Alawi, and Ko 1988 and Sture 1988<sup>1</sup>). The same phenomenon also has been observed in circular stress path tests performed in cubical devices, which also maintain a constant mean stress and octahedral shear/normal stress ratio (e.g., Lanier and Zitouni 1989). In any case, further investigations of loadings with continuous rotations are needed to explain the volumetric response.

<sup>1</sup>Personal Communication, 20 August 1988, S. Sture, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO.

## PART V: RECOMMENDATIONS FOR FUTURE WORK AND DEVELOPMENT

76. Continued use of the DSC will necessitate many modifications that will improve the device. However, based on the limited experiments thus far, further developmental work in the following areas would improve the practical application of the device:

- a. Improved strain measurements.
- b. Improved automation.
- c. Improved technique for alignment of shear sheets.
- d. Alternative to use of grease as lubricant to reduce machine viscosity.
- e. Comparative experiments with other shear devices.
- f. Improvements in techniques of specimen preparation including trimming undisturbed specimens.

### Strain measurement

77. At present, there are no satisfactory techniques for the DSC covering strains less than 0.5 percent, although good techniques do exist using mechanical/electrical devices for other apparatuses (Burland and Symes 1982) such as the hollow cylinder and conventional triaxial equipment. Because the measurement of the modulus (shear stiffness) at low strains is extremely important to engineers, there is a pressing need to develop a small-strain measurement technique suitable for the DSC.

### Automation

78. Any major improvement in automation requires the ability to use strain data for load control. At present, strains are measured from X-ray or photographic data after the test is complete. Thus, at best the device must be operated under load control. Because the relationship between applied boundary load and specimen stress depends on specimen distortions, even true stress control cannot be achieved accurately.

### Shear-sheet alignment

79. The use of the brass shear-sheet position indicator provides a simple, reliable, and accurate method to maintain alignment of the shear sheets. Unfortunately, positioning of the brass

piece between the shear sleeve and the normal-pressure bag introduces a significant nonuniformity on the specimen boundary. Comparison of monotonic tests ( $\psi = 0$ ) with and without the brass pieces in place indicates that their presence reduces the failure stress by approximately 15 percent. Either modification of the attachment of the brass piece to the specimen or its elimination altogether is needed to improve the uniformity of the boundary condition.

### Lubrication

80. The use of silicon grease as a friction-reducing media is a major variable in test results. Some of the problems that arise from its use are:

- a. For grease to be effective and thereby produce repeatable test data, each coating of grease must be uniform and have the same thickness. The required high viscosity of the grease makes this extremely difficult to accomplish.
- b. The rotating of the principal stress axes requires the adhesion of the shear sleeve to the specimen such that shear stresses can be applied to the specimen boundaries. Because grease prevents the bonding between surfaces it must be kept from contacting areas to be bonded. Incomplete bonding of the shear sleeve to the specimen causes the application of nonuniform shear stresses and therefore erratic test data. In general, the presence of exposed grease on so many of the test components inhibits freedom of movement within the device and complicates test setup and apparatus cleanup.
- c. The use of grease between the top plate and the specimen reduces the visibility of the grid which must be used to determine the induced strains when photographic techniques are used to measure strains. Blurring of the grid makes repeatable targeting of the grid difficult thereby reducing the accuracy of strain measurements.

Another type of lubricating technique which could eliminate either some or all of these difficulties would simplify procedures and improve the repeatability of test data.

### Comparative studies

81. The WES Soil Research Center has a hollow cylinder test device and is thus ideally suited to make an unbiased in-depth comparative study of the performance of these two pieces of equipment. At present, this situation is unique and offers a chance to help the geotechnical community in assessing the relative merits of the two apparatuses. Also comparative studies with other DSC devices based on different design details would help assess the quantitative accuracy of the data. In particular, the extensive data on Leighton Buzzard sand obtained using the CU DSC (Sture, Alawi, and Ko 1988) would serve as a good basis for such a study. Extending the

study to devices such as the cubical triaxial device would require consideration of appropriate constitutive relationships to relate the sand behavior under the different stress systems produced in the two types of devices; while such a study would be useful in extending knowledge of sand behavior, its use in equipment development would be limited.

### Specimen preparation

82. The pluviation technique has been used extensively by UCL for specimen preparation. This technique is limited by difficulty in achieving DSC specimens that are comparable with those of other apparatuses. For the DSC to be useful in more general research and practical applications, specimen preparations should be developed to include sedimentation, slurry consolidation, and wet tamping. In addition, trimming of reconstituted clay and undisturbed specimens have not been fully addressed. It is anticipated that reconstituted clays and undisturbed specimens could be trimmed using techniques similar to those developed for the original DSC by Germaine (1982).

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## APPENDIX A: FABRICATION OF RUBBERIZED COMPONENTS

### Chemical Constituents

#### Coagulant

A1. The primary purpose of the coagulant is to promote membrane formation during the dipping process. Without the coagulant it would be difficult to make thick membranes and rubber sheets. The coagulant is a solution of hydrated calcium nitrate and methanol. A full-strength solution is made by dissolving hydrated calcium nitrate,  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ , in methanol alcohol at a ratio of 3 to 2 by weight (approximately 594 g to 500 ml). The calcium nitrate must be slowly poured into the methanol and intermittently stirred until all the calcium nitrate is dissolved, a step that will probably take several hours. The solution should then be kept in a plastic container with an airtight cover; the size and shape of the container will depend on the dimensions of the membrane mandrel. Normally, a container having a capacity of approximately 20 l is suitable.

A2. A full-strength coagulant solution is only needed for thicker membranes such as those used for the normal-pressure bags in the DSC. For thin membranes (less than 1 mm) a half-strength solution should be used; this strength can be obtained by doubling the amount of methanol (a ratio of 3 to 4 by weight). It is convenient to keep these two strengths of coagulant available during any testing program.

#### Latex

A3. All membranes used in the DSC are fabricated from prevulcanized natural rubber latex (such as Dunlop A1-330). The latex must be stored in plastic airtight containers similar to those used for the coagulant. The container should be kept clean, and the latex periodically sieved through an open-weave polyester material or cheesecloth to remove impurities and small pieces of cured latex. After sieving, the latex must be left to stand for 12 to 24 hr to allow air bubbles to dissipate that were entrapped during the sieving operation. Because water evaporates during the dipping process, the liquid latex will slowly increase in viscosity over a period of time. To reduce the viscosity of the latex a small amount of distilled water can be added until the correct consistency is achieved (Wong and Arthur 1985b) <sup>1</sup>.

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<sup>1</sup>References cited in the appendix are included in the references at the end of the main text.

## Rubberized Components

### Specimen membrane

A4. Specimen membranes that have the required specimen dimensions needed for the DSC are formed on an aluminum mandrel. Prior to its use the entire mandrel must be thoroughly burnished with a domestic scouring powder and rinsed with water until complete wettability of its surface is achieved. The burnishing ensures that the mandrel will take a complete and even coating of both coagulant and latex. During subsequent uses, mandrels must be cleaned at intervals with a degreasing agent (trichlorethylene is suitable) to prevent the development of a protein film on the mandrel's surface that inhibits the chemical reaction between the latex and coagulant.

A5. After cleaning, the mandrel is dipped in a half-strength coagulant solution, and the excess solution is allowed to drain back into the container. The mandrel must have an even and complete coating of coagulant over its entire surface. If a complete coating of coagulant cannot be achieved, the mandrel will have to be recleaned. After coating, the mandrel is placed in an oven that is temperature controlled at 60° C to evaporate the methanol leaving calcium nitrate crystals. When the crystals can be seen forming on the mandrel's surface, it is removed from the oven and left to cool in a relatively dry atmosphere. Because calcium nitrate is hygroscopic, it may absorb enough water from a humid atmosphere to cause the coagulant to run on the mandrel's surface and produce at best a membrane of uneven thickness.

A6. Before dipping the mandrel in the liquid latex, the surface of the latex is skimmed to remove bubbles, particles, etc. The membrane mandrel is held at an angle (approximately 30 deg), while it is slowly dipped into the latex. The angle minimizes the formation of air bubbles on the mandrel's surface. After the mandrel is totally immersed, it is rotated steadily through 180 deg and then slowly lifted out of the latex at a similar angle to that of entry. The time of immersion will control the thickness of the membrane (thickness is also dependent on coagulant strength); trial and error may be necessary to obtain the desired membrane thickness. After removal of the mandrel from the latex, it is rotated slowly, allowing excess latex to drain off. This procedure should produce a membrane with uniform thickness. Any small defects in the membrane (defects are more likely to form at corners and edges) can be patched by applying a small amount of liquid latex to each defect. A small-diameter glass rod coated with liquid latex simplifies the patching procedure.

A7. The membrane should be allowed to dry slightly for 5 min before immersing the mandrel and membrane in water to leach out excess coagulant; flowing clean water should be

used during the leaching period (4 hr or longer). Removal of the excess coagulant makes the membranes waterproof and increases their elasticity and transparency. Subsequent to leaching, the membrane is cured in an oven at 60° C for up to 6 hr.

A8. The membrane can be removed from the mandrel by cutting away the excess membrane material from the back of the mandrel. Talcum powder can be used on the membrane to prevent it from adhering to itself. The membrane is slowly and carefully peeled off the mandrel; if talcum powder is not used care must be taken to prevent the membrane from adhering to itself. Hand or finger contact with the mandrel's bare surface should also be avoided to prevent contamination, which will require that the mandrel be cleaned before using it again.

A9. For longer shelf life, membranes should be stored in darkness at approximately 5° C (e.g. a refrigerator). If the mandrel is not to be used for some time, its cleanliness can be preserved by leaving it covered with a membrane and storing it in darkness at 5° C.

### Sealing rubber sheet

A10. The same procedure is used for the sealing rubber sheet as for the specimen membrane; a 200- by 250-mm plate mandrel is used, each side of the plate yielding one sheet. After a sheet is cured, a fine grid is drawn on its surface prior to its use as a sealing sheet.

### Vacuum line tubes

A11. Vacuum tubes are made using an aluminum rod (3-mm diam) as a mandrel. A procedure similar to that used for the specimen membrane is also used here except that the rod is immersed in latex for 1 min. To ease the stripping of the latex tube from the rod, talcum powder is applied to both the rubber and to fingers and the rubber is rolled towards one end of the rod.

### Reinforced pressure bags

A12. A rubber membrane can be reinforced by applying two layers of 100-percent polyester material to its surface. Polyester material is normally stiffer in one direction; the stiff direction of each layer must be positioned orthogonal to one another. For adequate reinforcement two layers of reinforcing material should be used.

A13. A normal-pressure bag mandrel is first dipped in half-strength coagulant and dried using the previously described procedure. It is then immersed in liquid latex for 2 min. The coagulated latex must be leached but does not have to be fully cured before it is reinforced. The reinforcing material is first laid on a flat surface. The mandrel is placed in the center of the

material (handle pointing upward) with the edges of the mandrel aligned parallel to the threads of the material. The material is then cut to a size such that when it is wrapped around the mandrel, it will extend approximately 6 mm beyond the mandrel's edges.

A14. To apply the material to the pressure bag, the mandrel is inverted and the material is placed centrally and squarely on the upturned surface. Evostik 9162 adhesive latex is poured onto both the material and the top of the mandrel. An aluminum or glass rod can be used to spread the adhesive latex evenly over the surface and to press the material firmly down onto the membrane, working outward from the middle of the face. After the top face is covered, slits may be cut in the reinforcing material diagonally inward at the corner. The slits will help in fitting the reinforcing material at each corner. If necessary, the material is trimmed at the four corners to a length that will allow approximately 6 mm of material to wrap around the edges and corners. However, care should be taken to ensure that there is adequate material to cover the bag's corners.

A15. Material at the edge is glued by starting at the middle of each edge and working toward each corner, making sure that there is plenty of material to overlap the corners. After all the material has been attached to the membrane, the rod is wiped clean and rolled on the reinforcement to ensure that the material is firmly attached to the membrane. The material should be completely covered by the adhesive latex.

A16. The same procedure is followed when applying the second layer of reinforcing fabric, ensuring that the stiff direction of the layers is orthogonal. After application of the final layer of reinforcing material, the finished pressure bag is dipped in latex to obtain a thin final coat, and it is then cured in an oven.

A17. To remove the reinforced bag from the mandrel, a cut is made around the mandrel's handle to form a round hole. The mandrel's handle is placed in a vise. Choosing the corner with the least reinforced area, the membrane is peeled away from the hole and it is rolled over the corner; some effort is required. This procedure is repeated for an adjacent corner. If removal of the membranes from the mandrel proves impossible, the reinforcement has been overlapped a little too far and a new pressure bag will have to be fabricated; there is no way to reduce overlapping of material at the corners.

## Shear sheets

A18. A special sailcloth-type material is used in the fabrication of the shear-sheet material. The material is stretched on a clean glass plate and held in place with tape. Latex is worked into the fabric with the excess latex being *squeezed* off. It is cured in air (not in an

oven). The surface next to the glass is smooth while the squeegeed surface has the texture of the cloth. It is important not to assemble the shear sheets such that two rough surfaces are in contact; a rough-to-smooth contact should always be maintained.

A19. The other components of shear sheets are fabricated from nonreinforced latex rubber. The stretching elements have a thickness of  $1.02 \pm 0.025$  mm and have a kaolin filler to prevent deterioration in the light. The shear sleeves are made by the regular dipping process; their final thickness is 0.6 mm.

A20. The rubberized cloth components of the daisy-chain shear sheets are cut to the required sizes and shapes using a knife-tipped soldering iron (approximately 25 watts). The soldering iron eliminates fraying of the cloth edges by melting the threads as it cuts.